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ROOM-TEMPERATURE SHEAR AND COMPRESSION TESTS OF STIFFENED PANELS WITH INTEGRAL OR ATTACHED COOLING CIRCUITS

By Marvin B. Dow and Ralph O. Whitley

Langley Research Center
Langley Station, Hampton, Va.

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SUMMARY

The results of tests on 22 Z-section-stiffened panels loaded in shear and compression are presented and discussed. The sheet used in the fabrication of 16 of the panels had cooling circuits attached to or made an integral part of the sheet. The panels were tested at room temperature with water flowing in the cooling circuits at the design values of inlet pressure and flow rate. The results indicated that the presence of the cooling circuits did not significantly penalize the load-carrying capability of the panels. Structural loads had little effect on the flow rate of water in the cooling circuits until severe sheet buckling at high load levels had occurred. Water leaks developed in the cooling circuits of a few panels before gross panel failure, but in no cases were the leaks caused by rupturing of the cooling circuits due to load. Supplemental tests showed that turbulent flow existed in the cooling circuits at the design values of inlet pressure and flow rate.

INTRODUCTION

The structures of aircraft and spacecraft currently envisioned will be exposed to thermal environments varying from moderate to severe. A portion of the heating associated with these environments will be absorbed by the load-carrying structure. For vehicles such as hypersonic boost-gliders, the temperature attained will be sufficient to cause serious loss of strength in the metals currently used in airframe construction. Structures fabricated of such metals can be utilized only if some form of thermal protection is provided to restrict the temperature rise of the metal.

One solution to the problem of maintaining the load-carrying structure at satisfactory operating temperatures might involve the use of multilayer construction. In this type of construction, protection from the airstream would be provided by a radiation shield and a layer of insulation. The heat which passed the insulation would be absorbed by liquid coolant carried in tubes attached to or made an integral part of the metal sheet used in fabrication of the load-carrying structure. Vehicles utilizing a cooled metal structure have several inherent advantages as compared with "hot structures" in which the structure operates at elevated temperature. Some of the advantages are:

(1) Maximum use may be made of available materials and fabrication techniques

(2) Airframe strength and rigidity are virtually unaffected by the thermal environment experienced by the vehicle

(3) Crew and equipment are protected from heating without the extensive use of separate cooling systems

Several formidable problems are involved in the use of an active liquid cooling system to provide thermal protection for the load-carrying structure of a vehicle. The cooling system and the load-carrying members must be structurally compatible. The reservoirs, pumps, piping, valves, and controls necessary to store and distribute the coolant make such a cooling system complex. Rigid quality control in the fabrication of structure and cooling system is essential since coolant leaks, with the resulting loss of structural cooling, cannot be tolerated. Redundancy in cooling-system components to safeguard against failure imposes a weight penalty on vehicle performance. Some of these problems, such as the structural compatibility of the cooling system and the load-carrying members, can be investigated through experimental testing.

This paper presents the results of shear and compression tests performed on stiffened panels, some of which had sheets designed for circulation of a liquid coolant. The test panels were representative wing and fuselage panels of a vehicle designed to utilize an active liquid cooling system. The purpose of the tests, which were conducted at room temperature, was to determine the structural strength of the panels in shear and compression and the structural compatibility of the cooling system and panel sheets.

SYMBOLS

E	Young's modulus, ksi
h	panel width, in.
Q	flow rate, gal/min
Δp	differential pressure, psi
$\bar{\gamma}$	average shear strain
δ	elongation, in.
$\bar{\epsilon}$	unit shortening, in./in.
$\bar{\sigma}$	average compressive stress due to applied load, ksi
$\bar{\tau}$	average shear stress due to applied load, ksi

TEST SPECIMENS AND TEST PROCEDURES

Test Specimens

The test specimens, designed and fabricated by the Bell Aerosystems Company, were 3- by 3-foot stiffened aluminum-alloy panels representative of wing and fuselage construction. Sixteen of the panels tested differed from conventional sheet-stiffener construction in that the sheets were fabricated with either integrally formed cooling circuits or attached cooling circuits. The remaining six panels were fabricated with plain sheets. These 6 panels furnish a basis for comparison of the structural behavior of the 16 panels having sheet cooling circuits.

The sheets for the panels having integrally formed cooling circuits in the skin, hereafter called tubed-sheet panels, were 2024-T4 aluminum alloy. The sheets were constructed by a process of metallurgically bonding two plain aluminum-alloy sheets, one of which had the pattern of the cooling circuit printed on the interface with a pattern parting agent. After bonding, the sheet was rolled to a nominal 0.040-inch gage. The cooling-circuit pattern was then inflated hydrostatically to form an integral system of headers and cooling passages inside the sheet. A photograph of a panel with integral cooling circuits formed in this manner is shown as figure 1. Inlets and outlets to permit the circulation of liquid coolants were provided by the connectors shown in the photograph of figure 2. Sheets constructed in the manner previously mentioned but which did not have the cooling circuit inflated were used in the fabrication of three plain-bonded-sheet comparison panels. Because of rolling width limitations, two separate sheets were required to obtain the 3-foot width. This resulted in each tubed-sheet panel having a splice in the center and two separate cooling circuits.

The sheet for the panels with attached cooling circuits, hereafter called tube-on-sheet panels, was fabricated by ribbon brazing aluminum tubing to one side of a plain 6951 aluminum-alloy sheet of nominal 0.032-inch gage. Three separate cooling circuits were provided for each tube-on-sheet panel. Inlet and outlet connections for liquid coolant circulation were provided by extending the tubing ends through the sheet to the stiffener side. A photograph of a typical panel fabricated in this manner is shown as figure 3. Plain sheets without the brazed-on tubing were used to fabricate three comparison panels.

The stiffeners on all panels were of Z-section, constructed of 2024-T6 aluminum alloy and formed by extrusion. Two sizes of stiffeners were used, depending on whether the panel was a representative wing or fuselage panel. The nominal dimensions of the stiffeners and both types of sheet cooling passages are shown in figure 4.

The test panels varied in materials and configuration as follows:

(1) Sheet material: 2024-T4 or 6951 aluminum alloy

(2) Type of sheet: tubed-sheet, tube-on-sheet, or plain sheet

(3) Stiffener spacing: 3 or 6 inches

(4) Orientation of cooling passages to stringers: normal or parallel

The materials and configurations of the test panels are summarized in table I. Tables II and III present some pertinent dimensions of the sheets used in fabricating the panels.

Test Procedures

Prior to testing, several resistance-type wire strain gages were mounted on both sides of the panel sheet and on the stiffeners by the manufacturer. Strains from the gages on the six panels without cooling circuits were autographically recorded during testing with a 24-channel strain recorder. Strains from the gages on the remaining panels were recorded on magnetic tape at discrete time intervals by the Langley central digital data recording facility.

All panels were loaded in the Langley 1,200,000-pound-capacity testing machine. Load was applied to the panels in accordance with a loading schedule furnished by the manufacturer. The load schedule called for loading the panels with an initial base load and then increasing the load in increments to panel failure. The base loads used were 1,000 pounds for the shear panels and 2,000 pounds for the compression panels. The loads were increased in increments with the first increment being 3,000 pounds followed by 4,000-pound increments for the shear panels and 5,000-pound increments for the compression panels. After each maximum, the load was decreased to the base load or some intermediate load, and then in the next loading cycle the load was increased one increment above the previous maximum. This procedure was continued until high load levels were reached at which time the load was no longer decreased after each load increment. Strain-gage readings were recorded continuously or at short time intervals. The load was held constant at the various load levels to permit reading and recording of other instrumentation.

The system for supplying water to panels with cooling circuits and the instrumentation for measuring cooling-circuit inlet pressure, flow rate, and differential pressure are shown schematically in figure 5 for tubed-sheet and tube-on-sheet panels.

For tubed-sheet panels, both cooling circuits were fully instrumented. Two of the three cooling circuits on each tube-on-sheet panel were fully instrumented. Only the inlet pressure on the third cooling circuit was measured. The rate of water flow for the third cooling circuit was established by using the averaged valve settings of the other two cooling circuits.

Visual pressure gages indicated the inlet pressure of each cooling circuit. The flow rate through each fully instrumented cooling circuit was measured by turbine-type flow meters while differential pressure transducers connected across the inlet and outlet measured the differential pressure. The output of these instruments was displayed visually for control purposes and the same output was recorded by the Langley central digital data recording facility.

The procedure in each test of a panel having cooling circuits was to establish the inlet pressure and flow rate of water in the cooling circuits at the design values after the base load had been applied. The design values were as follows:

Inlet pressure, psig	50
Flow per circuit, gal/min:	
Tubed sheet	1
Tube on sheet	0.7

The pressure differential across the cooling circuit obtained at the design values of inlet pressure and flow rate was the initial-base-load pressure differential. Test requirements called for maintaining the cooling-circuit pressure differential and inlet pressure at the initial-base-load value until cooling-circuit deformation at the high load levels made this impossible. The flow rate was allowed to vary from its initial value if necessary in order to maintain inlet pressure and differential pressure at their initial values.

As the panels were successively loaded and unloaded, cooling-circuit deformation caused the flow rate and differential pressure to change. Since the water pump used was not a constant-head pump, there was also some variation in inlet pressure. Variations in these coolant parameters, while load was being applied or removed, were corrected by valve adjustments in order to maintain the inlet pressure and differential pressure at approximately initial-base-load values.

At each load level, the load was held constant and careful adjustments were made to reestablish the initial-base-load inlet pressure and differential pressure. When this was accomplished, the data from all instrumentation were recorded. The panel was then unloaded to the base load or an intermediate load and the data were again recorded. This procedure was repeated until cooling-circuit deformation at high load levels made it impossible to reestablish the initial-base-load inlet pressure and differential pressure. When cooling circuits developed leaks during testing, water flow to the leaking circuit was stopped and the test continued to gross panel failure.

Supplemental measurements of coolant parameters were made on three of the panels tested. These tests, performed with an inlet pressure of 50 psig, involved the determination of the differential pressure across the cooling circuits as the flow rate was varied from 20 to 120 percent of the initial-base-load flow rate.

<u>Shear tests</u>.- The test setup for the shear tests is shown in the photograph of figure 6. The shear panels were bolted along the edges to a heavy steel frame which had pin-connected corners as shown in the photograph of figure 7. Load was applied to the panels along a diagonal by two clevises attached to the testing machine. (See fig. 7.) Elongation of the tension diagonal during loading was measured by an extension-rod—dial-gage device shown in figures 1, 3, and 7.

<u>Compression tests</u>.- The test setup for the compression tests was similar to that for shear tests except for the method of load application. The ends of the compression panels were ground flat and parallel prior to testing and the panels were carefully alined in the testing machine to insure uniform bearing between

the ends of the panels and the platens of the testing machine. Lateral restraint for all panels was provided by bolting the two structural ribs shown in figure 2 to steel beams rigidly attached to the testing machine. Overall shortening of the distance between testing-machine platens was measured by the averaged output of resistance-type wire strain gages mounted on a pair of small cantilever beams whose deflection was equal to the shortening of the distance between platens. Lateral deflection of the panels at the structural ribs was measured by dial gages mounted at six locations opposite the ribs. These measuring devices are shown in the photograph of figure 8.

RESULTS AND DISCUSSION

Results of the shear and compression tests are given in tables II to VII and in figures 9 and 10. The results of the supplemental tests performed on three of the test panels are given in figure 11. These test results will be discussed separately.

Shear Tests

The failure load, average failing shear stress, and ultimate shear load in kips/in. for the shear panels are given in table II. Tables IV and V give the percent of variation from the initial-base-load value of the water flow rate at various load levels for the tubed-sheet and tube-on-sheet panels, respectively. The cause of cooling-circuit leaking and the load at which the flow of water to leaking circuits was stopped are given for the applicable panels in tables IV and V. The load levels in tables IV and V are shown in the same order in which shear loads were applied to the panels. The variation of the average shear stress due to applied load with the average shear strain for the test panels is given in figure 9.

From the results given in table IV, it can be seen that the effect of shear loading on the tubed-sheet panels was to decrease the rate of water flow in the cooling circuits. This was caused by restrictions in the cooling circuits resulting from sheet buckling with attendant crippling of cooling-circuit headers and passages. The amount of permanent change in the flow rate after unloading to the base load was small until high load levels were reached, at which time the panels were severely buckled. The small percentage of variation in the base-load flow rate after unloading from the lower load levels resulted from the inability to reestablish the initial-base-load values exactly with the equipment used and not from the effects of shear loading.

The results of table V show that shear loading had little effect on the flow rate of water in the cooling circuits of tube-on-sheet panels. This result follows from the fact that the tubes were able to accommodate themselves to the sheet buckles with little effect on the tube cross sections.

The values for average shear stress shown in the curves of figure 9 were calculated from the applied loads. For this purpose, the sheet only was considered to be effective in carrying the shear loads. The ends of the panel stiffeners were not in contact with the sides of the steel loading frame. This forced the sheet to carry the shear loads and resulted in the tests being primarily a measure of the shear-carrying ability of the panel sheets. Strain measurements indicated that the panel stiffeners picked up some load after the sheet was severely buckled. In all the panels tested, the stiffener flange next to the sheet was adequate in preventing the sheet buckles from extending across the sheet-stiffener rivet lines.

Values for shear strain were calculated from measurements of the elongation of the tension diagonal made at each load level. For these calculations, it was assumed that the sides of the heavy steel shear frame did not bend or change in length from load. This meant that the shear frame remained a rhombus at all loads and the shear strain was calculated from the geometry of the test panel as follows: (See ref. 1.)

$$\bar{\gamma} = \frac{\sqrt{2}\,\delta}{h}$$

where

δ elongation of the tension diagonal

h panel width

Strain measurements were obtained from strain rosettes mounted on the panel sheets. These strain rosettes were mounted on only one side of the sheets and therefore would not account for the bending out of plane of the sheet as a result of buckling. For this reason, these strain measurements were not used in preparing figure 9.

From the curves of figure 9, it can be seen that the stiffener spacing had little effect on the shear stiffness of the panels with cooling circuits. The plain-sheet panels with a 6-inch stiffener spacing have less shear stiffness than those with a 3-inch stiffener spacing. The tube-on-sheet panels with cooling circuits had considerably more shear stiffness for both stiffener spacings than plain-sheet panels 8 and 14. Similar behavior was also true of the tubed-sheet panels with a 6-inch stiffener spacing. Panels 15 and 17 which had cooling passages oriented parallel to the stiffeners had slightly less shear stiffness than the panels with cooling passages oriented normal to the stiffeners.

The severe sheet buckling at high load levels resulted in crippling of headers and cooling passages in the tubed-sheet panels. The increased severity of this crippling with increase in load is shown in the photographs of figure 12. The tubes of the tube-on-sheet panels were better able to accommodate the sheet buckling and as a result were not damaged until panel failure occurred.

The failure of the panels in each case resulted from sheet tearing. The tearing began at rivet lines on the edges of the panels and then propagated inward and, in some cases, along the edges of the panels. The failure patterns of a tubed-sheet and a tube-on-sheet panel are shown in the photographs of figure 13.

Compression Tests

The failure load, average compressive stress at failure, and ultimate compressive load in kips/in. for the compression panels are given in table III. Tables VI and VII give the percent of variation from the initial-base-load value of the water flow rate at the various load levels for the tubed-sheet and tube-on-sheet panels, respectively. The load levels in tables VI and VII are shown in the same order in which compression loads were applied to the panels. The variation of the average compressive stress due to applied load with the unit shortening of the test panels is given in figure 10.

The results given in table VI show that the effect of compression loads was much less severe than shear loads on the flow rate of water in the cooling circuits of tubed-sheet panels. It is interesting to note that high compression load tended to increase the flow rate. This effect was probably caused by an increase in the cross-sectional area of headers and passages due to compression loads.

The results given in table VII show that compression loads had little effect on the flow rate of water in the cooling circuits of tube-on-sheet panels. The apparent exception to this for the upper cooling circuit of panel 11b was due to errors in reestablishing the initial flow rate. It should be noted that there was little variation in the flow rate after the erroneous settings.

The load-shortening curves of figure 10 were prepared from load-shortening data corrected to zero strain. The slope of all the curves is substantially less than the accepted E of 10,000,000 psi for aluminum alloys, with the exception of panel 9. The tubes forming the cooling circuits of tube-on-sheet panels were not considered effective in carrying compression loads and the area used in calculating average stress included only the sheet and stiffeners. Panel 9 had cooling passages oriented parallel to the stiffeners and located midway between stiffeners. These cooling passages were probably more effective in stiffening the sheet and preventing local sheet buckling than cooling passages oriented normal to the stiffeners. Also the water pressure in the cooling passages of panel 9 produced tension stresses in the cooling-passage walls and the immediately adjoining sheet which had to be overcome by compression loading before compressive stresses were present in these regions of the panel sheet. These effects were also present in panel 3 but for reasons given in the discussion of failure modes there was no noticeable difference in the load-shortening curve of this panel as compared with the load-shortening curves of tubed-sheet panels with cooling passages oriented normal to the stiffeners. The presence of splices in the center of the tubed-sheet panels with possible looseness around rivet holes may have resulted in increased panel shortening. The reason for the low values of E obtained from the load-shortening curves of the tube-on-sheet panels, with the exception of panel 9, is not known. The orientation of the cooling passages with the stiffeners, with the exception of panel 9 as previously discussed, did not appear to affect the strength of the panels.

As in the shear panels, the stiffener flange next to the sheet was adequate in preventing sheet buckling from extending across the sheet-stiffener rivet lines. Sheet buckling from compression loading did not cause severe crippling of headers and cooling passages on the tubed-sheet panels as in the shear tests.

Deep permanent buckles in the panel sheet were not evident even after failure. The effect of compression loading on the tube-on-sheet panel was likewise less severe than shear loading.

The lateral deflection of the panels measured at the structural ribs was extremely small at all loads. This was expected since the ribs were secured to stiff supports rigidly attached to the testing machine.

All panels, except 3, 5a, and 5b, failed in the wrinkling mode. (See ref. 2.) A typical failure in this mode is shown in the photograph of figure 14. Panels 3, 5a, and 5b appeared to have failed in the interrivet mode as discussed in reference 2. Failure occurred adjacent to the center splice on panels 5a and 5b and at the cooling circuit header on panel 3 where the rivet spacing was greatest. Also, it should be noted that the sheet of panel 3 at the greatest rivet spacing had initial crookedness resulting from the cooling-circuit header located at that point. Failures in the interrivet mode are shown in the photographs of figure 15.

Failure occurred in the 12-inch space between structural ribs on all panels except 3 and 11a. This was expected for panel 3 since failure occurred at a point of maximum rivet spacing which was near the ends of the panel. The reason the failure of panel 11a occurred outside the region between structural ribs is not known. It should be noted that panel 11b, which was fabricated in an identical manner, failed in the space between structural ribs.

Supplemental Tests of Cooling Circuits

The variation of differential pressure with flow rate at a constant inlet pressure of 50 psig for the cooling circuits of three panels is shown in figure 11. The linear portions of the curves indicate that turbulent flow conditions were obtained for the design flow rates, that is, 1.0 gal/min for the tubed-sheet panels and 0.7 gal/min for the tube-on-sheet panels. (See ref. 3.) The difference in the differential pressure at any value of flow rate for cooling circuits on the same panel as well as for the cooling circuits on different panels indicates substantial variation in the flow characteristics of the various cooling circuits. The slopes of the linear portion of the curves varied less among the various panel cooling circuits than did the differential pressure with the exception of one cooling circuit on panel 15. The slope of the linear portion of this curve is substantially different from the others. This difference might have been caused by a partial obstruction in the cooling circuit but the exact reason is not known.

CONCLUDING REMARKS

Tests demonstrate that an active liquid cooling system could be built into the load-carrying structural components of a vehicle. The presence of the cooling circuits did not penalize the load-carrying capabilities of the panels, and in some cases actually increased the stiffness of the panels. The orientation of the cooling circuits with respect to the stiffeners did not appear to have any significant effect on the strength of the panels. The cooling circuits on the tubed-sheet panels were not permanently damaged until high load levels were reached. The crippling of headers and cooling passages from sheet buckling increased progressively at high load levels. The cooling circuits on the tube-on-sheet panels were not adversely affected by loading. Although leaks developed in the cooling circuits of some panels prior to gross panel failure, the leaks were not caused by rupturing of cooling passages or headers due to load.

Langley Research Center,
National Aeronautics and Space Administration,
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TABLE I.- TEST-PANEL DESCRIPTION AND CONFIGURATION

Panel	Type of loading	Stiffener spacing, in.	Design section	Orientation of cooling passages with respect to stiffeners	Type of construction	Type of aluminum alloy
1	Compression	3	Wing	No passages	Plain bonded sheet	2024-T4
2	Shear	3	Wing	No passages	Plain bonded sheet	2024-T4
3	Compression	3	Wing	Parallel	Tubed sheet	2024-T4
5a, 5b	Compression	3	Wing	Normal	Tubed sheet	2024-T4
6a, 6b	Shear	3	Wing	Normal	Tubed sheet	2024-T4
7	Compression	3	Wing	No passages	Plain sheet	6951
8	Shear	3	Wing	No passages	Plain sheet	6951
9	Compression	3	Wing	Parallel	Tube on sheet	6951
11a, 11b	Compression	3	Wing	Normal	Tube on sheet	6951
12a, 12b	Shear	3	Wing	Normal	Tube on sheet	6951
13	Shear	6	Fuselage	No passages	Plain bonded sheet	2024-T4
14	Shear	6	Fuselage	No passages	Plain sheet	6951
15	Shear	6	Fuselage	Parallel	Tubed sheet	2024-T4
16a, 16b	Shear	6	Fuselage	Normal	Tubed sheet	2024-T4
17	Shear	6	Fuselage	Parallel	Tube on sheet	6951
18a, 18b	Shear	6	Fuselage	Normal	Tube on sheet	6951

TABLE II.- DIMENSIONS AND TEST RESULTS OF SHEAR PANELS

Panel	Average sheet thickness, in.	Panel width, in.	Cross-sectional area of sheet, sq. in.	Failure load, kips	Average shear stress at failure, ksi	Ultimate shear load, kips/in.
2	0.0436	41.5	1.81	58.55	22.8	0.977
6a	.0427	41.5	1.77	57.30	22.9	.976
6b	.0424	41.5	1.76	57.50	23.1	.981
8	.0395	41.5	1.64	35.80	15.4	.610
12a	.0308	41.5	1.28	29.65	16.4	.605
12b	.0313	41.5	1.30	28.70	15.6	.489
13	.0441	41.5	1.83	55.00	21.3	.938
14	.0371	41.5	1.54	37.1	17.0	.631
15	.0441	41.5	1.83	55.05	21.5	.945
16a	.0429	41.5	1.78	53.95	21.4	.920
16b	.0419	41.5	1.74	52.95	21.5	.902
17	.0304	41.5	1.26	29.4	16.5	.501
18a	.0318	41.5	1.34	31.95	16.8	.545
18b	.0304	41.5	1.26	30.09	16.9	.513

TABLE III.- DIMENSIONS AND TEST RESULTS OF COMPRESSION PANELS

Panel	Average sheet thickness, in.	Overall panel length, in.	Cross-sectional area of sheet and stiffeners, sq in.	Failure load, kips	Average failing stress, ksi	Ultimate compressive loading, kips/in.
1	0.0488	36.6	3.39	78.5	23.2	2.145
3	.0420	36.6	3.13	74.5	23.8	2.035
5a	.0419	36.6	3.15	74.2	23.6	2.025
5b	.0426	36.6	3.16	76.1	24.1	2.080
7	.0310	36.6	2.72	71.8	26.4	1.960
9	.0306	36.6	2.62	71.3	26.8	1.950
11a	.0312	36.6	2.68	67.9	25.3	1.855
11b	.0309	36.6	2.66	68.9	25.9	1.880

TABLE IV.- VARIATION OF COOLANT FLOW WITH LOAD FOR

TUBED-SHEET SHEAR PANELS

Panel	Load level, kips	Percent of failure load	Percent of change in Q from initial-base-load value	
			Upper[a] cooling circuit	Lower[a] cooling circuit
6a	[b]1	1.8	0.0	0.0
	4	7.0	-1.4	1.7
	1	1.8	-1.1	.5
	12	21.0	-.8	1.3
	1	1.8	-1.0	1.4
	16	27.9	.0	.7
	1	1.8	-.8	.4
	20	34.9	-1.1	1.4
	8	14.0	-.8	1.3
	24	41.9	-.6	.7
	8	14.0	-1.1	1.3
	28	48.8	-1.0	1.6
	8	14.0	-.8	1.5
	32	55.8	-.4	2.1
	1	1.8	-.7	1.6
	36	62.8	-1.3	1.6
	40	69.8	-.8	-3.6
	44	76.8	-1.5	-3.8
	48	83.7	-11.3	-25.9
6b	[b]1	1.7	0.0	0.0
	4	7.0	.2	-.3
	1	1.7	-.3	-.5
	12	20.9	.9	-.4
	1	1.7	.6	.4
	16	27.8	.6	.8
	1	1.7	-.3	.7
	20	34.8	-.5	.5
	8	13.9	-.5	.2
	24	41.7	-.6	.6
	8	13.9	-.1	.8
	28	48.7	1.5	-.2
	8	13.9	1.7	.4
	32	55.7	.9	1.4
	1	1.7	1.3	.5
	40	69.6	2.0	.8

[a]Refers to position of cooling circuit with panel in test position. (See fig. 1.)

[b]Initial flow condition established at this load. Inlet pressure = 50 psig; nominal Q = 1.0 gal/min.

TABLE IV.- VARIATION OF COOLANT FLOW WITH LOAD FOR

TUBED-SHEET SHEAR PANELS - Continued

Panel	Load level, kips	Percent of failure load	Percent of change in Q from initial-base-load value	
			Upper[a] cooling circuit	Lower[a] cooling circuit
6b	44	76.6	2.3	-0.5
	48	83.5	-5.0	-22.9
	1	1.7	1.0	1.0
	52	90.5	-7.1	-36.1
15	[b]1	1.8	0.0	0.0
	4	7.2	.2	-.2
	1	1.8	.0	-.2
	12	21.6	-.7	-.3
	1	1.8	1.2	.0
	16	28.8	.0	-.7
	1	1.8	1.7	-.1
	20	36.0	1.0	-1.1
	1	1.8	-1.0	.1
	24	43.2	-9.6	-2.0
	1	1.8	3.3	.4
	28	50.4	-17.3	-3.6
	1	1.8	3.5	1.6
	32	57.6	-32.6	-6.0
	1	1.8	2.3	-.9
	36	64.8	-43.9	-11.9
	1	1.8	-1.9	-2.2
	40	72.0	-52.1	-19.1
	1	1.8	-6.5	-7.8
	44	79.2	-63.6	-30.7
	1	1.8	-19.0	-16.5
	48	81.4	-63.9	-51.3
	1	1.8	-26.6	-37.7
16a	[b]1	1.8	0.0	0.0
	4	7.4	-.6	-.7
	1	1.8	-.6	-1.6
	12	22.2	.2	.3
	1	1.8	.5	.7
	16	29.6	.2	-1.4
	1	1.8	.5	.1

[a]Refers to position of cooling circuit with panel in test position. (See fig. 1.)

[b]Initial flow condition established at this load. Inlet pressure = 50 psig; nominal Q = 1.0 gal/min.

TABLE IV.- VARIATION OF COOLANT FLOW WITH LOAD FOR

TUBED-SHEET SHEAR PANELS - Concluded

Panel	Load level, kips	Percent of failure load	Percent of change in Q from initial-base-load value	
			Upper[a] cooling circuit	Lower[a] cooling circuit
16a	20	37.0	0.2	-1.6
	8	14.8	.2	-.4
	24	44.5	-.5	-4.2
	8	14.8	.3	-2.0
	28	52.0	-1.5	-4.8
	8	14.8	.5	-1.4
	32	59.3	-3.3	-8.1
	1	1.85	.4	-1.4
	36	66.8	-3.5	-10.3
	40	74.2	-12.8	-21.5
	44	81.5	-18.9	-31.4
	48	89.0	-39.2	-54.5
16b	[b]1	1.9	0.0	0.0
	4	7.6	-.3	-.1
	1	1.9	.0	.3
	12	22.6	-.7	-.6
	1	1.9	.2	-.1
	16	30.2	-.5	.3
	1	1.9	.8	.1
	20	37.8	-.8	.7
	1	1.9	1.6	.7
	24	45.3	-.6	-.6
	1	1.9	.0	.3
	28	52.9	-1.9	Junction of connector and cooling circuit leaking, flow stopped at 28 kips.
	1	1.9	.1	
	32	60.5	-3.2	
	1	1.9	.3	
	36	68.0	-6.5	
	1	1.9	-.5	
			Junction of connector and cooling circuit leaking, flow stopped at 40 kips.	

[a]Refers to position of cooling circuit with panel in test position. (See fig. 1.)

[b]Initial flow condition established at this load.

Inlet pressure = 50 psig; nominal Q = 1.0 gal/min.

TABLE V.- VARIATION OF COOLANT FLOW WITH LOAD FOR

TUBE-ON-SHEET SHEAR PANELS

Panel	Load level, kips	Percent of failure load	Percent of change in Q from initial-base-load value	
			Upper[a] cooling circuit	Lower[a] cooling circuit
12a	[b]1	3.4	0.0	0.0
	4	13.5	-.6	.5
	1	3.4	.2	-.3
	12	40.5	.6	-.4
	1	3.4	-.4	-.6
	16	54.0	1.1	.5
	1	3.4	-.1	-.4
	20	67.5	.9	-.5
	1	3.4	1.0	.6
	24	81.0	.4	.4
	1	3.4	.1	-.2
	28	94.5	.3	.6
	1	3.4	.0	-.2
12b	[b]1	3.5	0.0	0.0
	4	13.9	.6	.9
	1	3.5	.5	1.0
	12	41.8	.2	.7
	1	3.5	.2	.8
	16	55.8	.0	.8
	1	3.5	-.6	.6
	20	69.7	.0	.5
	1	3.5	.2	.6
	24	85.0	.4	.6
	1	3.5	.9	1.0
	28	97.5	.3	.1
17	[b]1	3.4	0.0	0.0
	4	13.6	-.5	-.7
	1	3.4	-.6	.5
	12	40.8	-.7	.4
	1	3.4	-.6	.2
	16	54.5	-.4	.5
	1	3.4	.4	.0
	20	68.0	-1.0	.2
	1	3.4	-.9	.3
	24	81.7	-.6	.5

[a]Refers to position of cooling circuit with panel in test position. (See fig. 3.)

[b]Initial flow conditions established at this load. Inlet pressure = 50 psig; nominal Q = 0.7 gal/min.

TABLE V.- VARIATION OF COOLANT FLOW WITH LOAD FOR

TUBE-ON-SHEET SHEAR PANELS - Concluded

Panel	Load level, kips	Percent of failure load	Percent of change in Q from initial-base-load value	
			Upper[a] cooling circuit	Lower[a] cooling circuit
17	1	3.4	-1.3	0.3
	28	95.3	-1.6	Break in tubing, flow stopped at 28 kips.
	1	3.4	-1.2	
18a	[b]1	3.1	0.0	0.0
	4	12.5	-.3	.9
	1	3.1	-.4	1.2
	12	37.6	-.2	.5
	1	3.1	-.1	-.5
	16	50.0	-.1	-.5
	1	3.1	.0	-1.2
	20	62.6	.0	.8
	1	3.1	-.1	-2.8
	24	75.1	-.1	.5
	1	3.1	-.2	-3.2
	28	87.6	.7	-3.0
	1	3.1	.5	-.2
18b	[b]1	3.3	0.0	0.0
	4		.3	-.3
	1	3.3	.0	.2
	12	39.8	.0	.1
	1	3.3	-.8	-.2
	16	53.1	.2	.7
	1	3.3	-.3	.2
	20	66.5	.1	.3
	1	3.3	.2	.3
	24	79.8	-.5	-.6
	1	3.3	-.5	-.3
	28	93.0	-1.5	1.0
	1	3.3	-1.3	-.7

[a]Refers to position of cooling circuit with panel in test position. (See fig. 3.)

[b]Initial flow conditions established at this load. Inlet pressure = 50 psig; nominal Q = 0.7 gal/min.

TABLE VI.- VARIATION OF COOLANT FLOW WITH LOAD FOR

TUBED-SHEET COMPRESSION PANELS

Panel	Load level, kips	Percent of failure load	Percent of change in Q from initial-base-load value	
			Left[a] cooling circuit	Right[a] cooling circuit
3	[b]2	2.7	0.0	0.0
	5	6.7	.5	.7
	2	2.7	.5	.6
	15	20.2	.6	.2
	2	2.7	-.9	.2
	20	26.8	.8	.7
	2	2.7	.1	.0
	25	33.6	-.1	1.0
	2	2.7	-.9	.8
	30	40.3	.5	1.5
	2	2.7	-.7	.1
	35	47.0	.8	1.6
	2	2.7	-.4	.0
	40	53.7	.6	1.7
	2	2.7	-.5	1.1
	45	60.5	1.4	2.3
	2	2.7	.3	1.2
	50	67.1	1.0	2.1
	55	73.9	.3	.9
	60	80.5	.7	2.3
	2	2.7	-.6	1.8
			Upper[a] cooling circuit	Lower[a] cooling circuit
5a	[b]2	2.7	0.0	0.0
	5	6.7	-.2	-.6
	2	2.7	.9	.1
	15	20.2	1.0	.6
	2	2.7	.1	-.8
	20	27.0	2.1	.7
	2	2.7	.4	.2
	25	33.7	2.2	1.9
	2	2.7	-.4	.1

[a]Refers to position of cooling circuit with panel in test position. (See fig. 15.)

[b]Initial flow conditions established at this load. Inlet pressure = 50 psig; nominal Q = 1.0 gal/min.

TABLE VI.- VARIATION OF COOLANT FLOW WITH LOAD FOR

TUBED-SHEET COMPRESSION PANELS - Concluded

Panel	Load level, kips	Percent of failure load	Percent of change in Q from initial-base-load value	
			Upper[a] cooling circuit	Lower[a] cooling circuit
5a	30	40.4	2.5	3.3
	2	2.7	.2	-.6
	35	47.1	3.2	2.9
	2	2.7	.8	-.1
	40	53.0	3.7	3.4
	2	2.7	.2	.1
	45	60.6	1.7	5.5
	2	2.7	1.4	1.7
	50	67.4	3.5	6.2
	55	74.1	5.1	6.7
	60	80.9	4.2	8.5
	2	2.7	1.4	-.3
5b	[b]2	2.6	0.0	0.0
	5	6.6	.5	.7
	2	2.6	.2	.3
	15	19.7	2.2	1.0
	2	2.6	.4	.7
	20	26.3	2.5	2.1
	2	2.6	.8	1.1
	25	32.8	4.1	3.3
	2	2.6	.1	1.6
	30	39.4	5.3	3.6
	2	2.6	.3	.6
	35	46.0	5.6	2.8
	2	2.6	1.3	.6
	40	52.6	-.4	3.4
	2	2.6	1.4	1.6
	45	59.1	7.4	5.7
	2	2.6	1.2	-.5
	50	65.7	8.0	3.3
	55	72.3	8.0	3.8
	60	78.8	6.3	3.5
	2	2.6	.8	2.9

[a]Refers to position of cooling circuit with panel in test position. (See fig. 15.)

[b]Initial flow conditions established at this load. Inlet pressure = 50 psig; nominal Q = 1.0 gal/min.

TABLE VII.- VARIATION OF COOLANT FLOW WITH LOAD FOR

TUBE-ON-SHEET COMPRESSION PANELS

Panel	Load level, kips	Percent of failure load	Percent of change in Q from initial-base-load value	
			Left[a] cooling circuit	Right[a] cooling circuit
[b]9	[c]2	2.8	0.0	0.0
	5	7.0	.9	.9
	2	2.8	.9	-.5
	15	21.0	.8	-.4
	2	2.8	1.2	.0
	20	28.0	.9	.2
	2	2.8	1.2	.3
	25	35.1	1.2	.3
	2	2.8	.9	.3
	30	42.1	1.1	.1
	2	2.8	1.2	.1
	35	49.1	1.0	.2
	2	2.8	.5	.2
	40	56.1	.0	-.8
	2	2.8	.8	.0
	45	63.1	1.0	.2
	2	2.8	1.0	.1
	50	70.1	1.3	.4
	55	77.1	.6	.1
	60	84.1	.8	.2
	2	2.8	.6	.1
			Upper[a] cooling circuit	Lower[a] cooling circuit
11a	[c]2	2.9	0.0	0.0
	5	7.4	-.1	-.4
	2	2.9	-.3	.5
	15	22.1	.6	.5
	2	2.9	.3	.9
	20	29.4	-.3	1.1
	2	2.9	.8	1.9

[a]Refers to position of cooling circuit with panel in test position. (See figs. 8 and 14.)

[b]The third cooling circuit developed leaks in tubing at the beginning of the testing. Panel was tested with no flow in third cooling circuit.

[c]Initial flow conditions established at this load.

Inlet pressure = 50 psig; nominal Q = 0.7 gal/min.

TABLE VII.- VARIATION OF COOLANT FLOW WITH LOAD FOR

TUBE-ON-SHEET COMPRESSION PANELS - Concluded

Panel	Load level, kips	Percent of failure load	Percent of change in Q from initial-base-load value	
			Upper[a] cooling circuit	Lower[a] cooling circuit
11a	25	36.8	-.7	1.0
	2	2.9	-.4	1.2
	30	44.2	-.7	.5
	2	2.9	-.4	1.5
	35	51.5	.0	2.0
	2	2.9	.4	1.8
	40	58.9	.9	1.3
	2	2.9	.9	.7
	45	66.3	-.1	1.2
	2	2.9	.5	2.0
	50	73.6	-.6	1.0
	55	81.0	.1	1.4
	60	88.4	.4	1.9
	2	2.9	.4	1.8
11b	[c]2	2.9	0.0	0.0
	5	7.3	-.3	-.4
	2	2.9	-.4	.5
	15	21.8	.6	1.0
	2	2.9	1.1	1.1
	20	29.0	-11.1	-.3
	2	2.9	-12.0	-.3
	25	26.3	8.3	.9
	2	2.9	8.3	.8
	30	43.5	8.5	-.3
	2	2.9	8.8	.8
	35	50.8	8.3	-.1
	2	2.9	9.0	.8
	40	58.0	8.2	.2
	2	2.9	8.9	.1
	45	65.3	10.7	.8
	2	2.9	9.5	1.4
	50	72.5	10.5	1.0
	55	79.8	10.4	1.4
	60	87.1	10.2	1.3
	2	2.9	10.0	-.3

[a]Refers to position of cooling circuit with panel in test position. (See figs. 8 and 14.)

[c]Initial flow conditions established at this load. Inlet pressure = 50 psig; nominal Q = 0.7 gal/min.

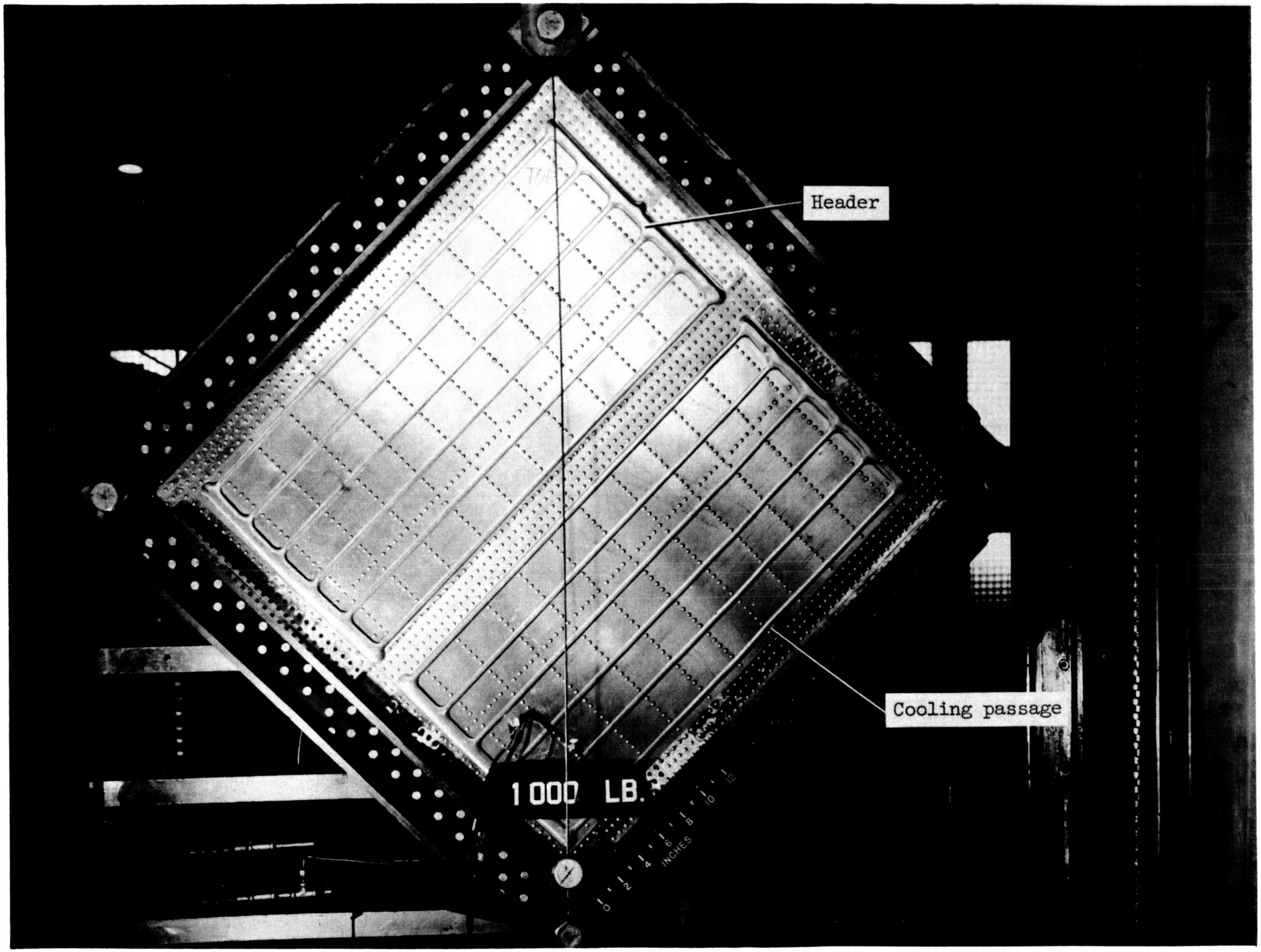
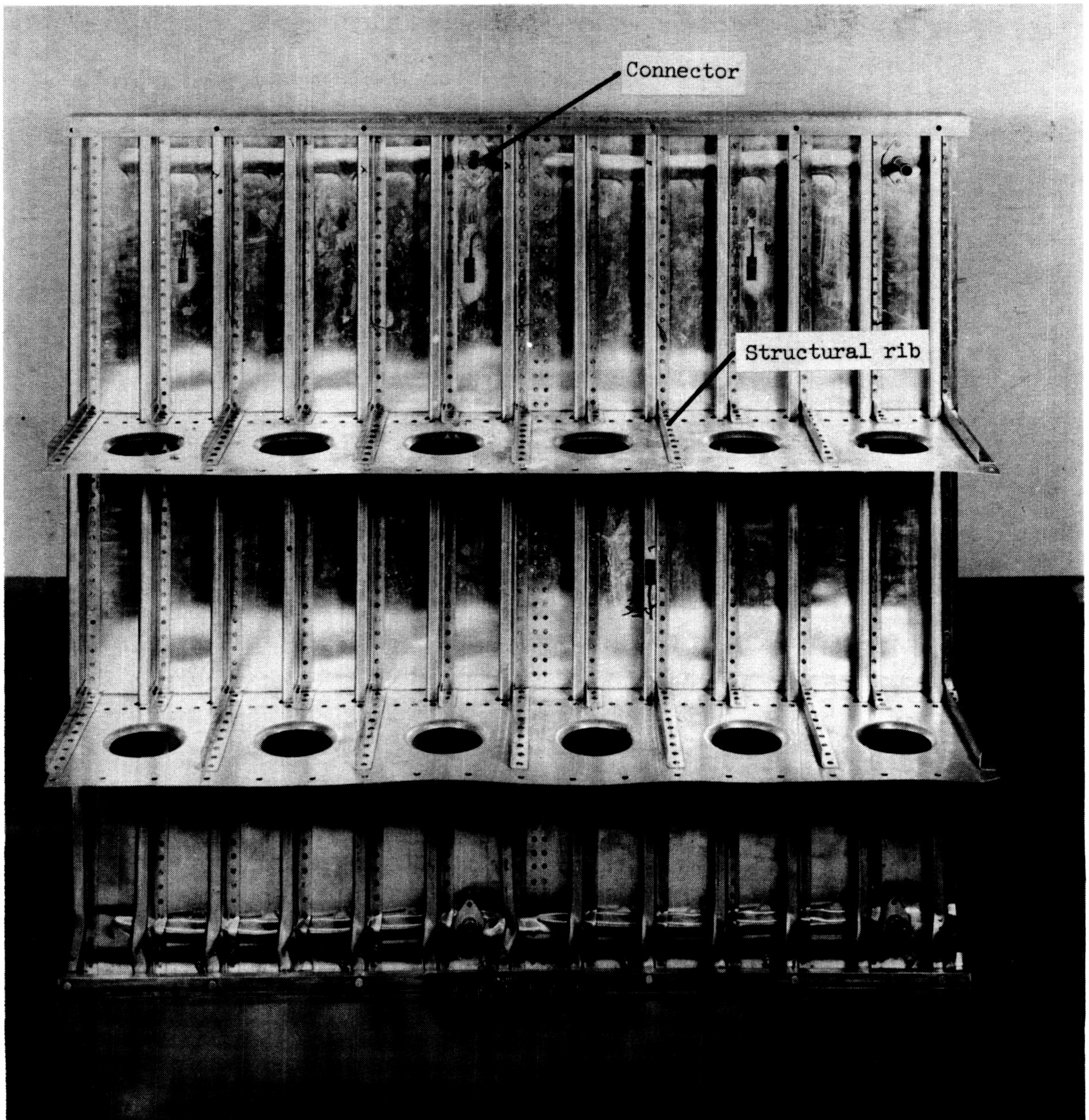


Figure 1.- Tubed-sheet panel with cooling circuits. L-60-4935



L-61-6372

Figure 2.- Compression panel after failure showing tubed-sheet connectors and structural ribs.

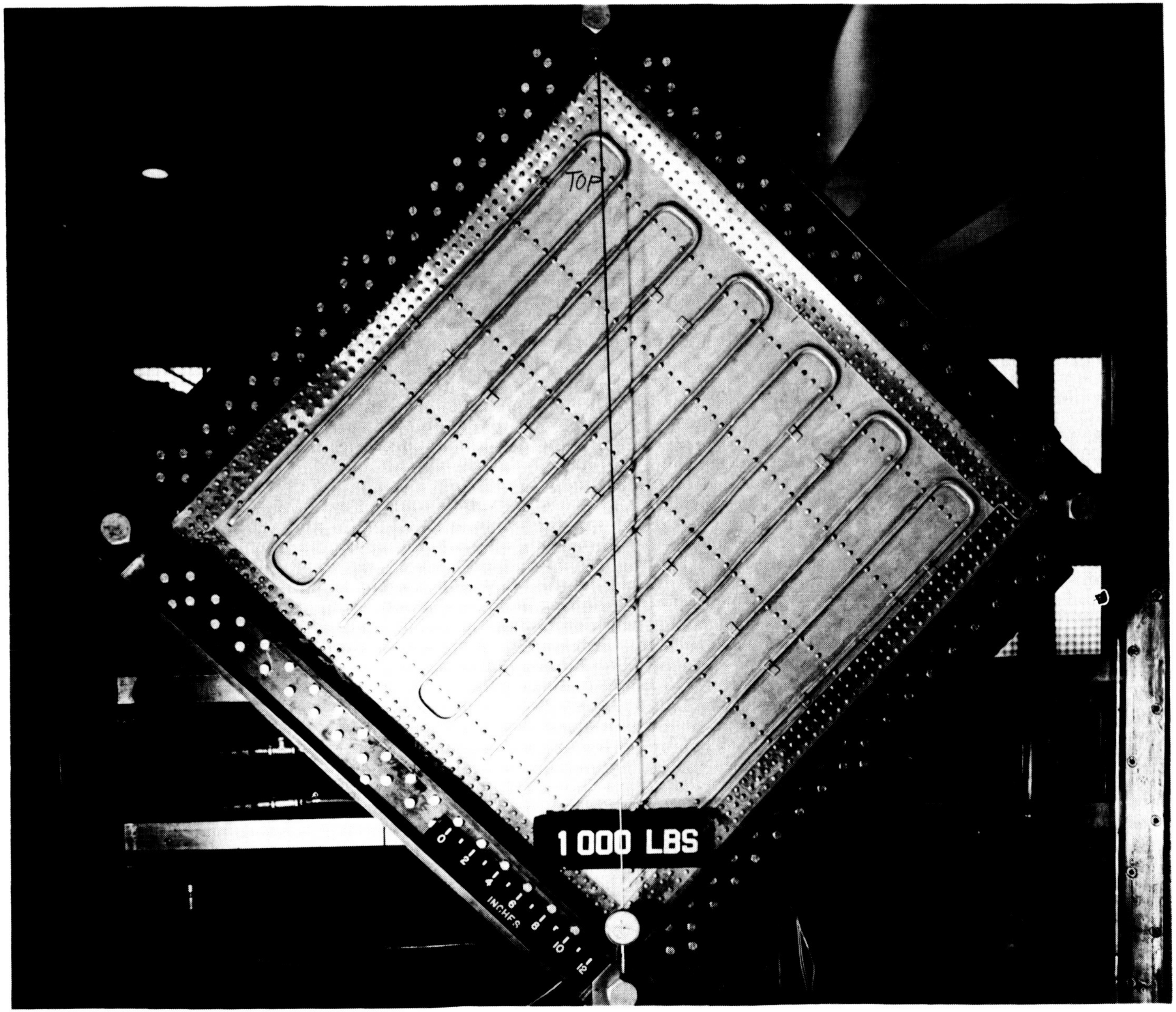
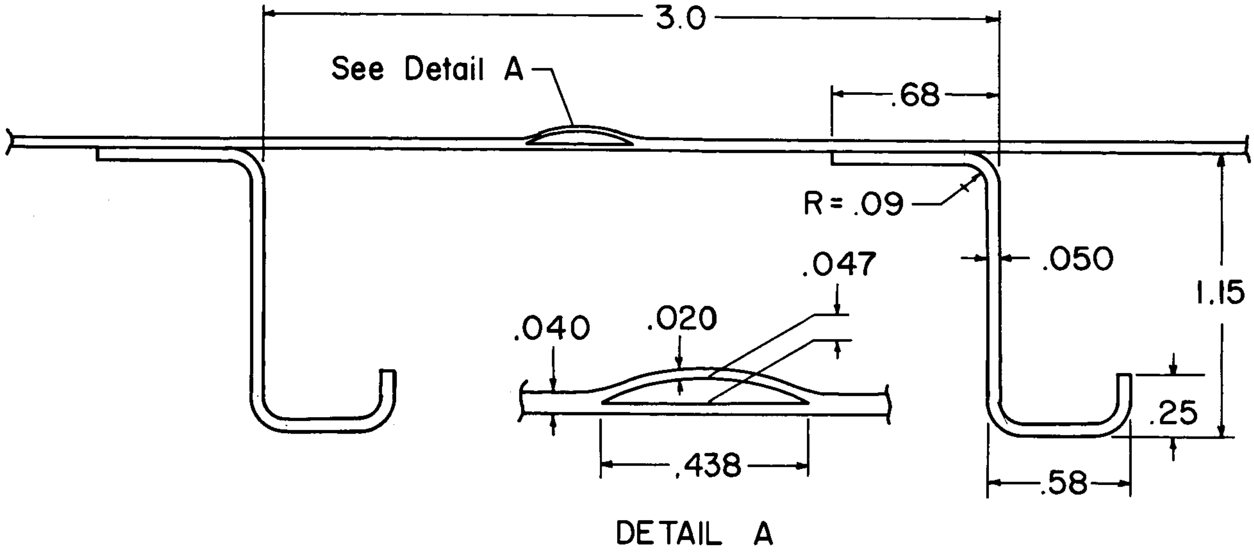
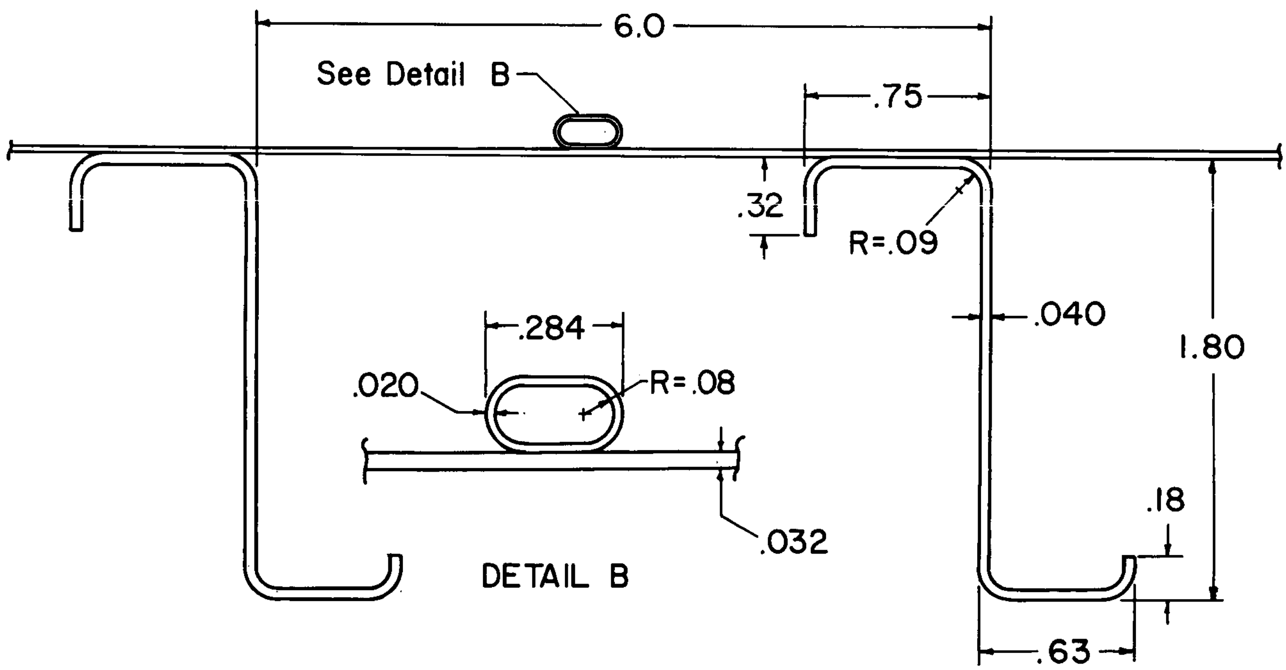


Figure 3.- Tube-on-sheet panel with cooling circuits. L-60-5114

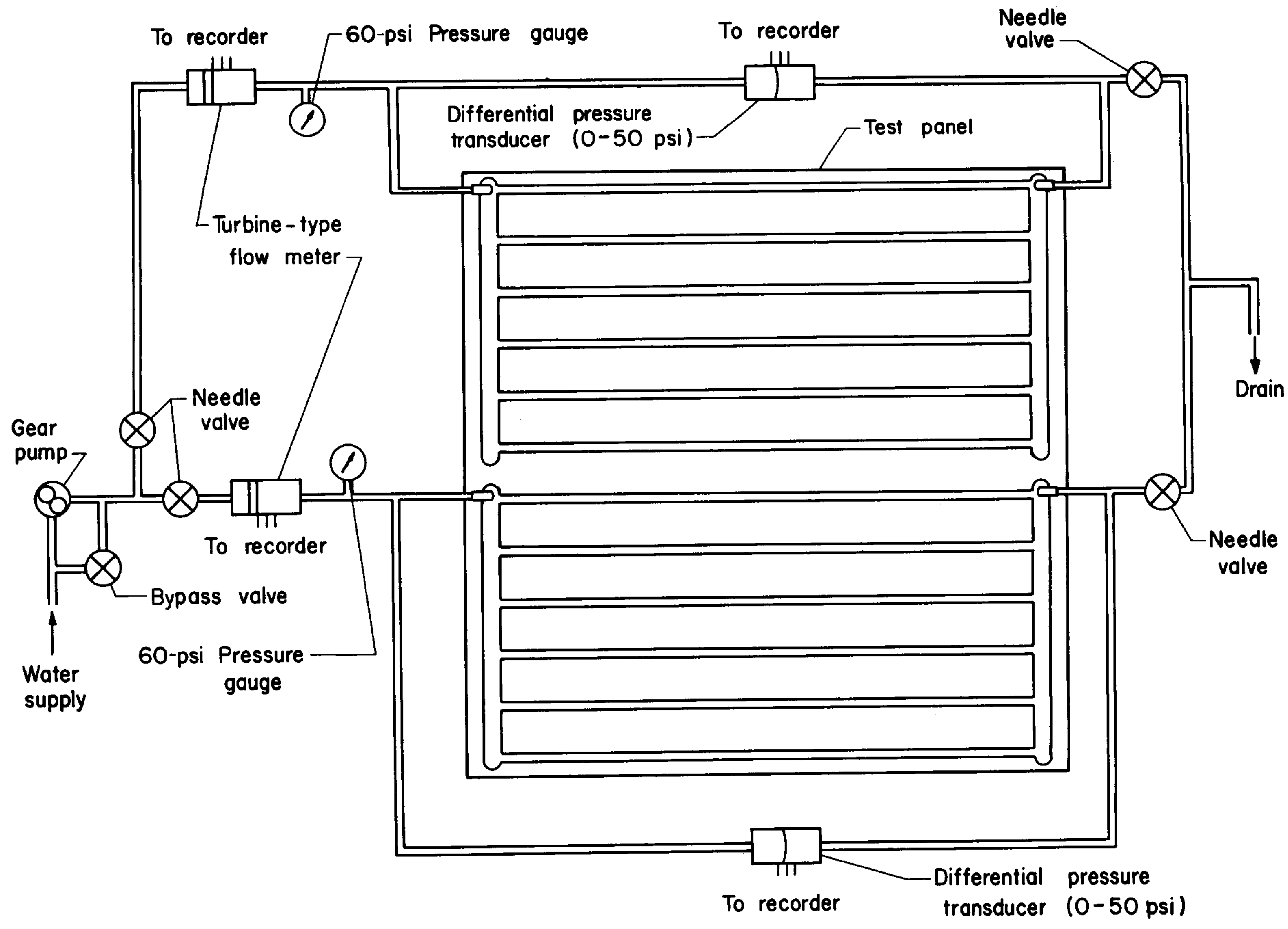


(a) Wing-section stiffeners and tubed-sheet cooling passages.



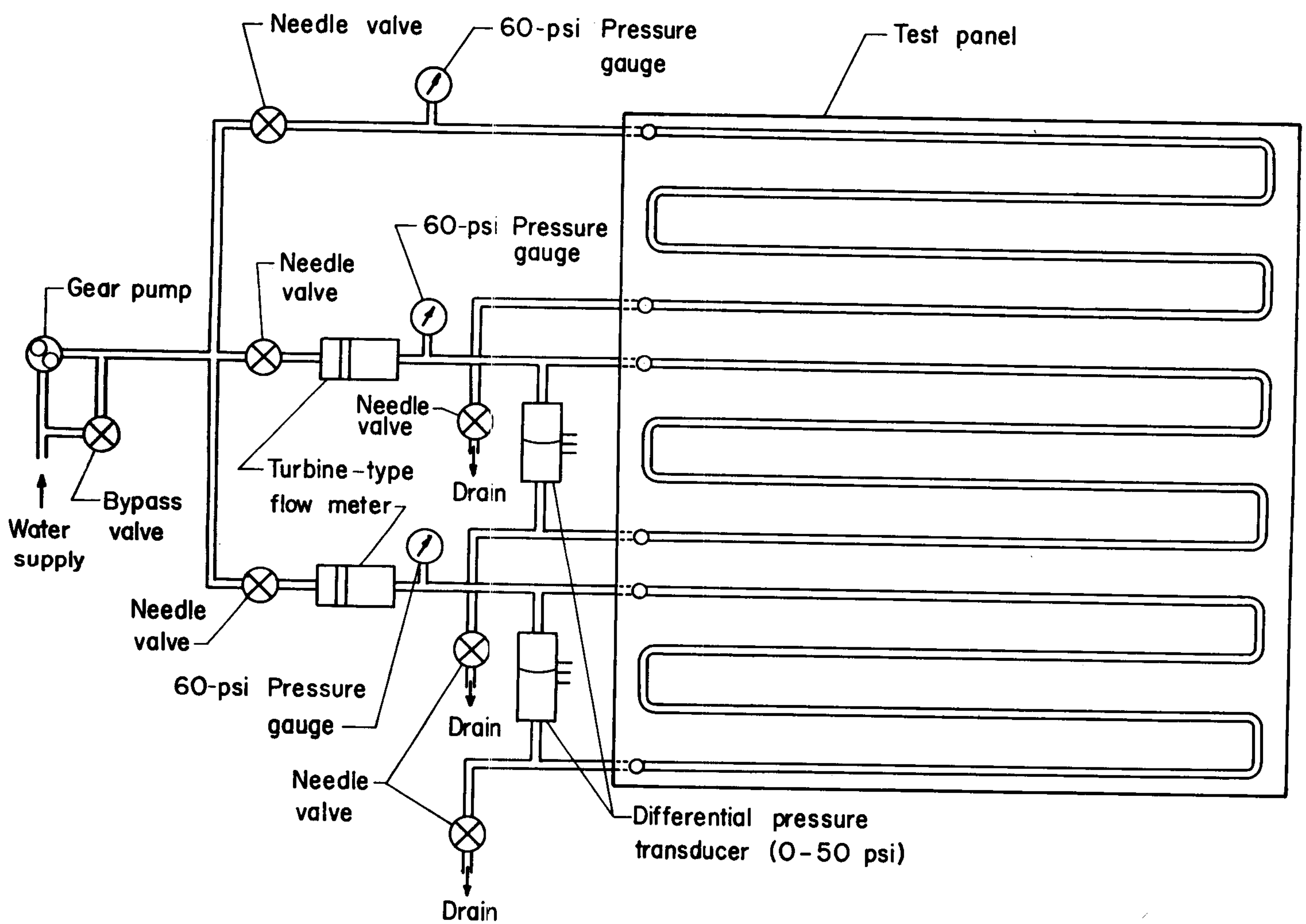
(b) Fuselage-section stiffeners and tube-on-sheet cooling passages.

Figure 4.- Dimensions of stiffeners and cooling-passage cross sections.



(a) Tubed-sheet panels.

Figure 5.- Flow and pressure instrumentation.



(b) Tube-on-sheet panels.

Figure 5.- Concluded.

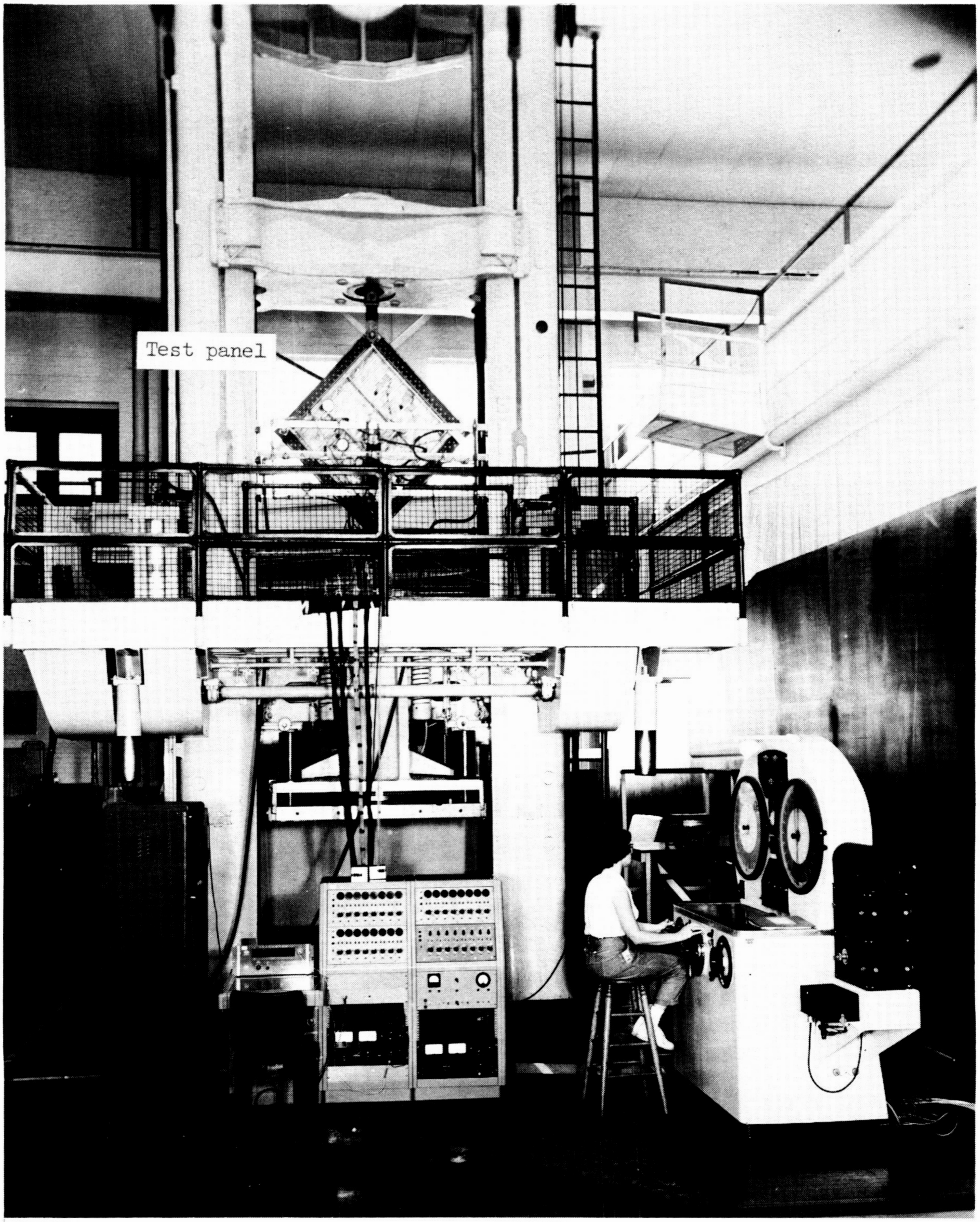


Figure 6.- Setup for shear tests. L-60-5373

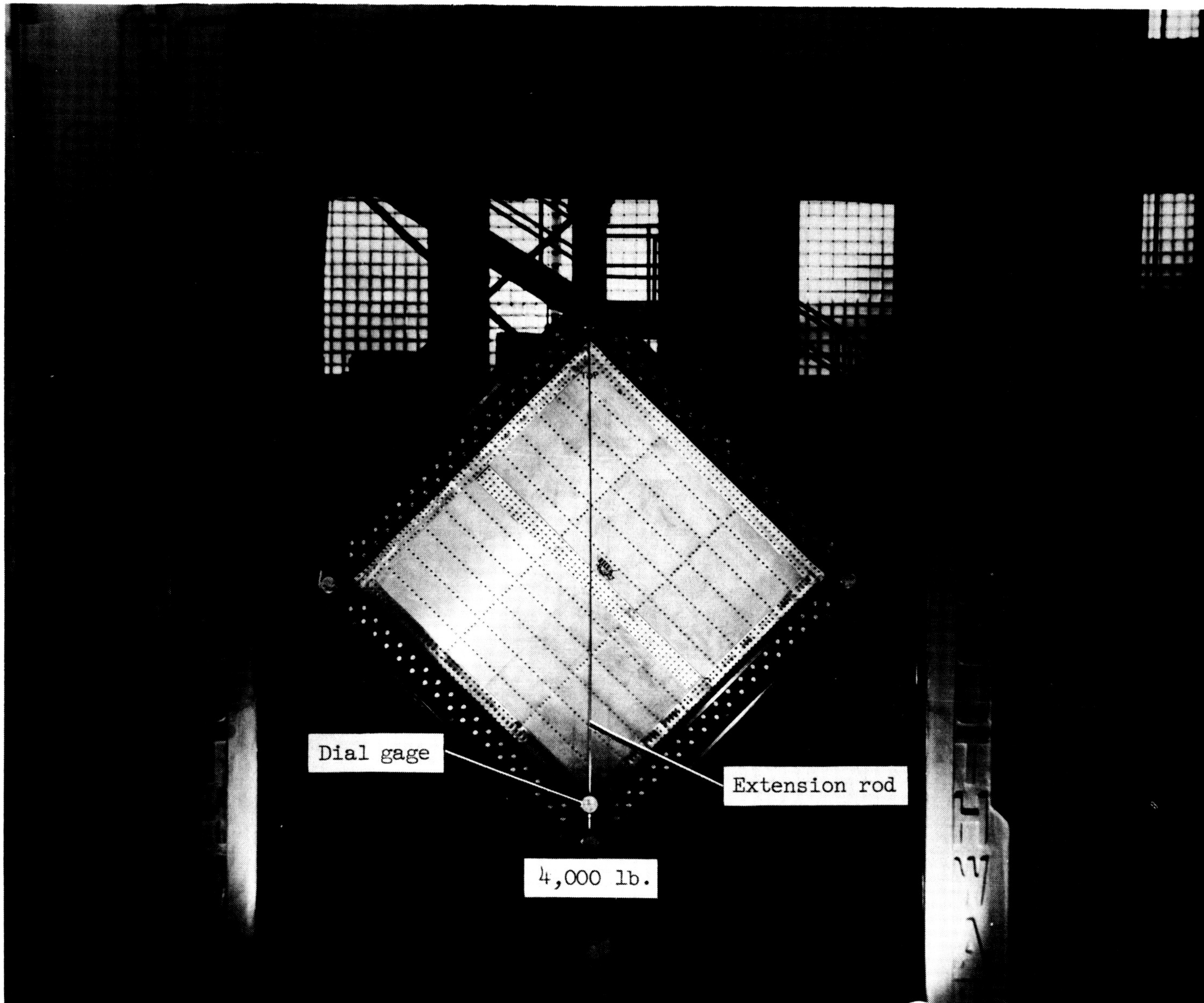


Figure 7.- Method of applying load to shear panels. L-60-3716

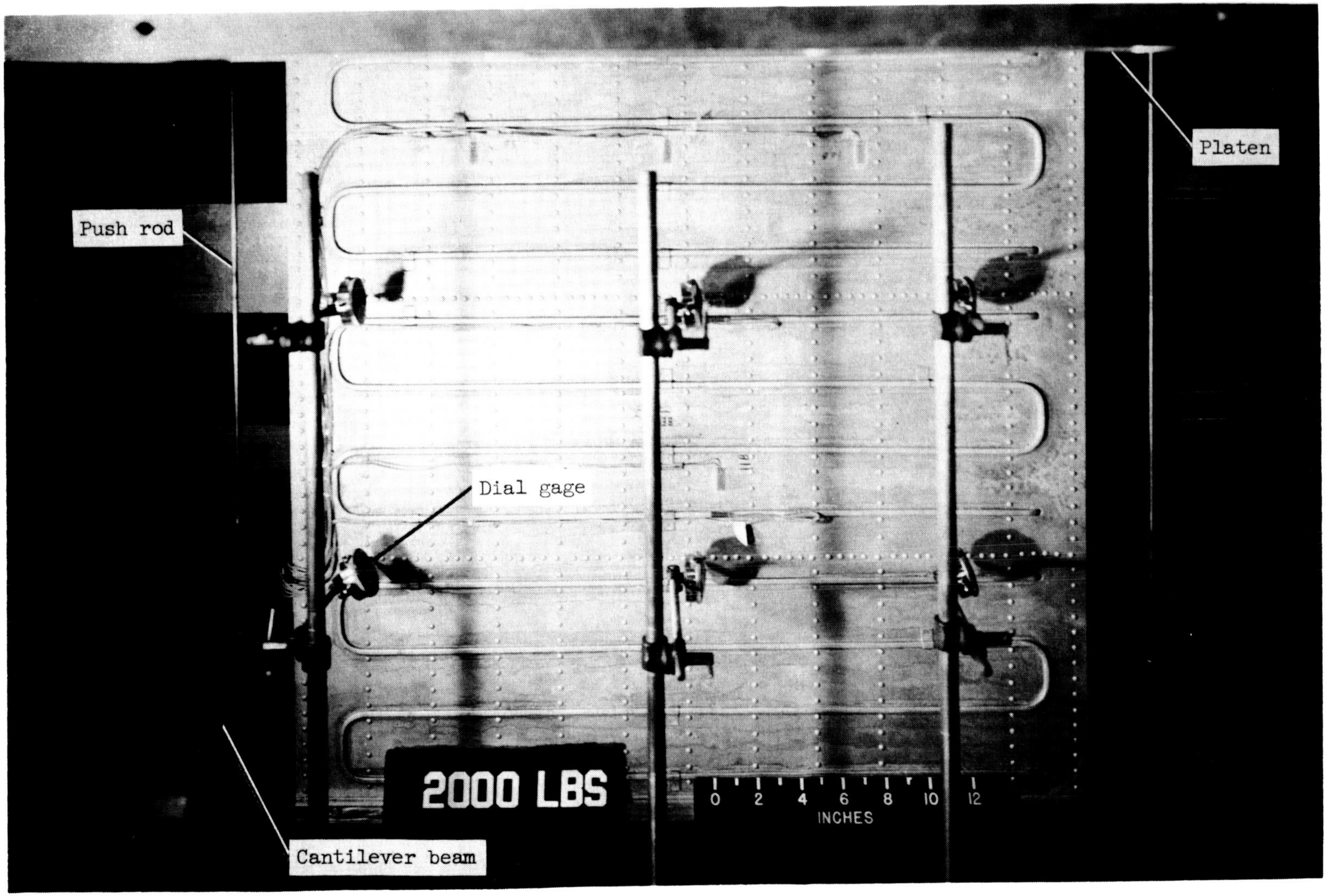
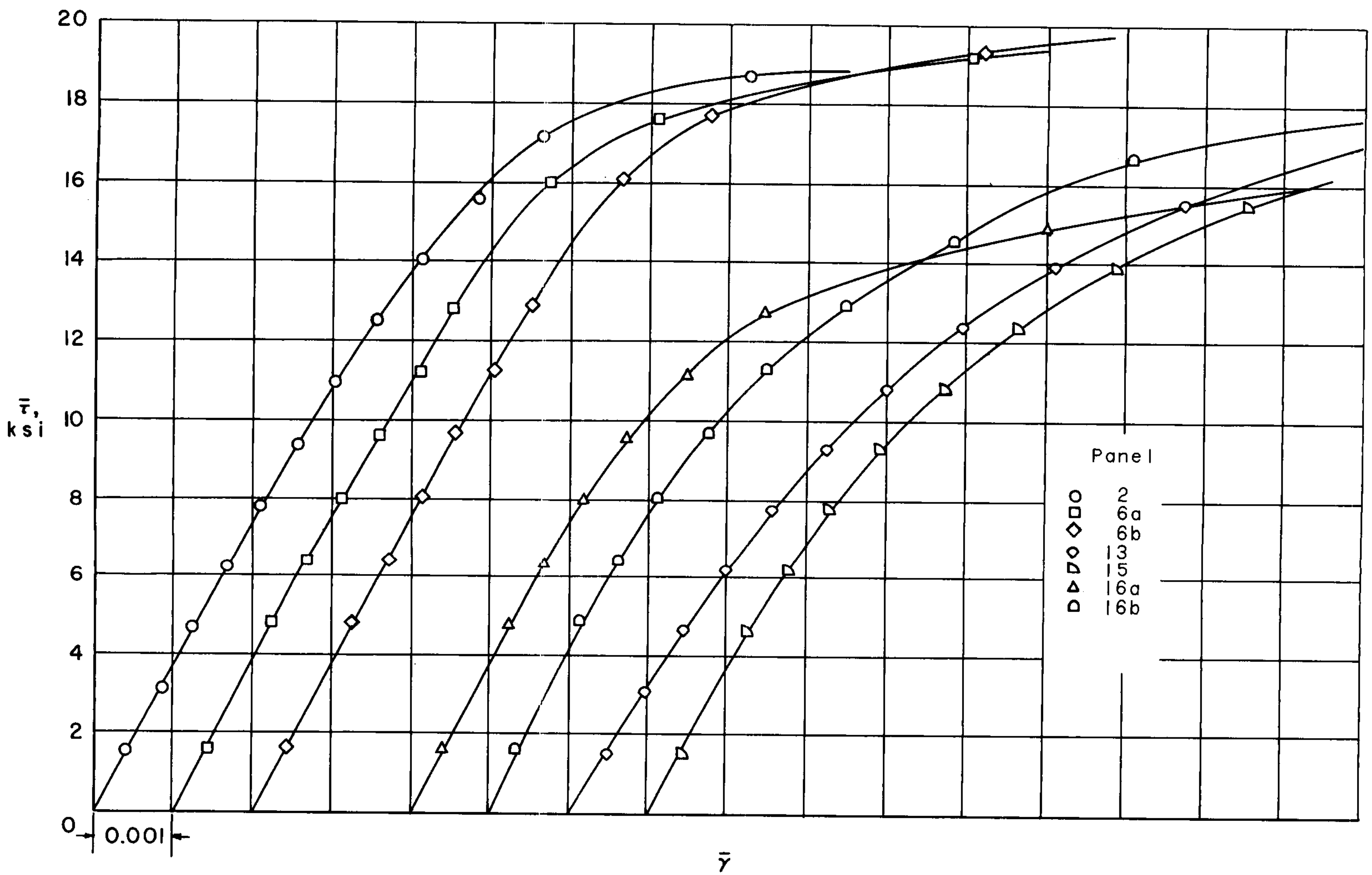
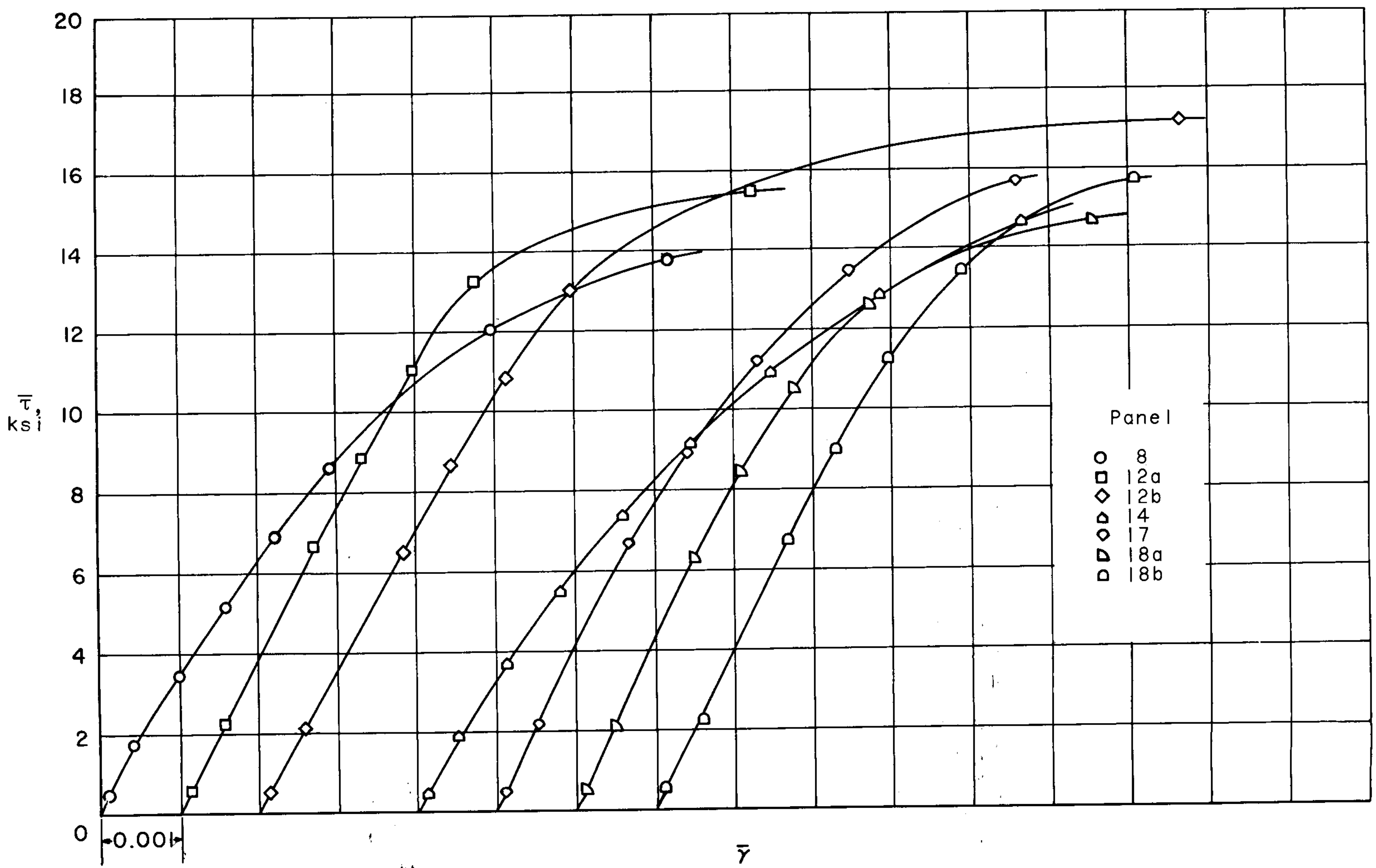


Figure 8.- Setup for compression tests. L-60-5678



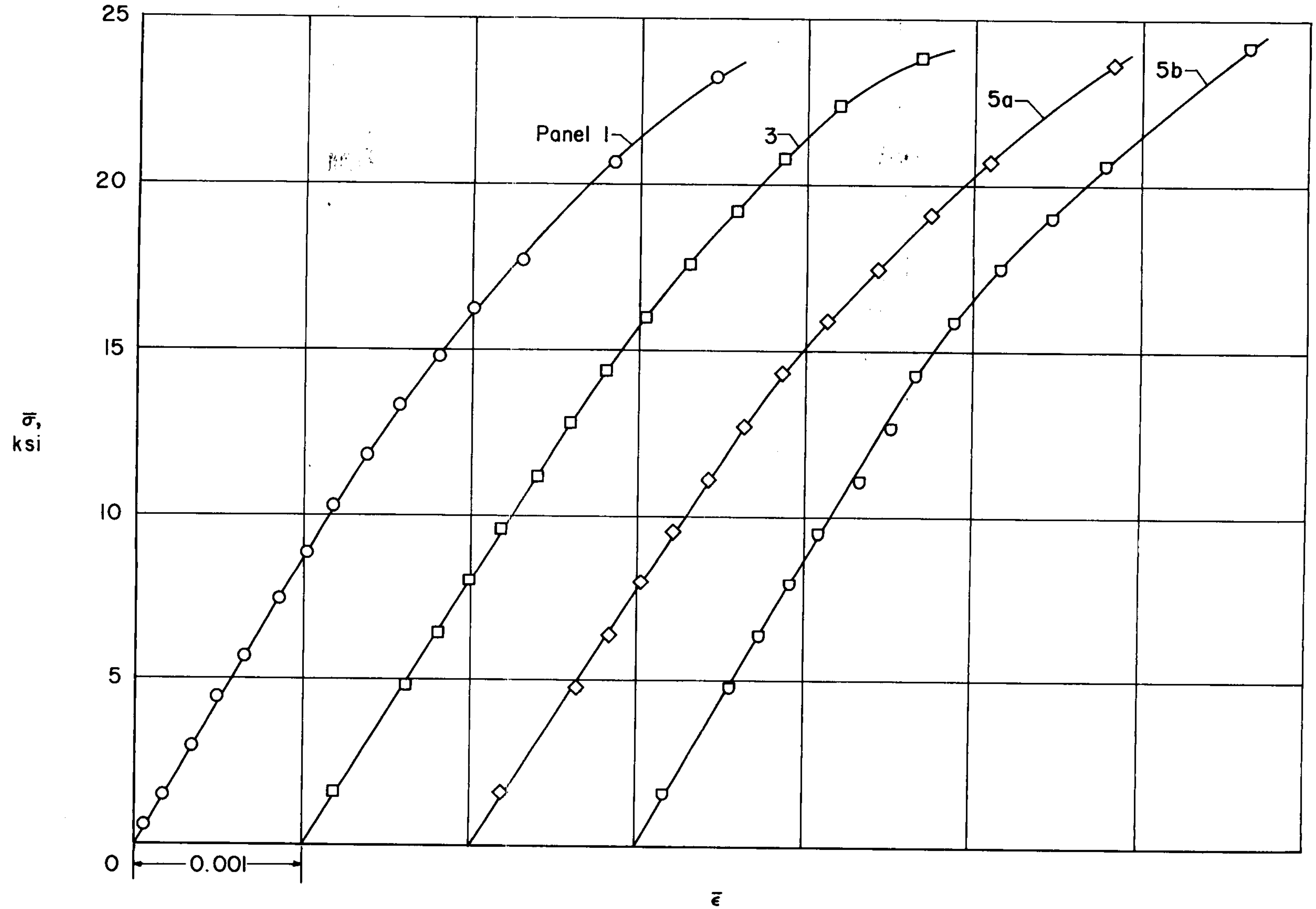
(a) Tubed-sheet panels.

Figure 9.- Shear stress-strain curves.



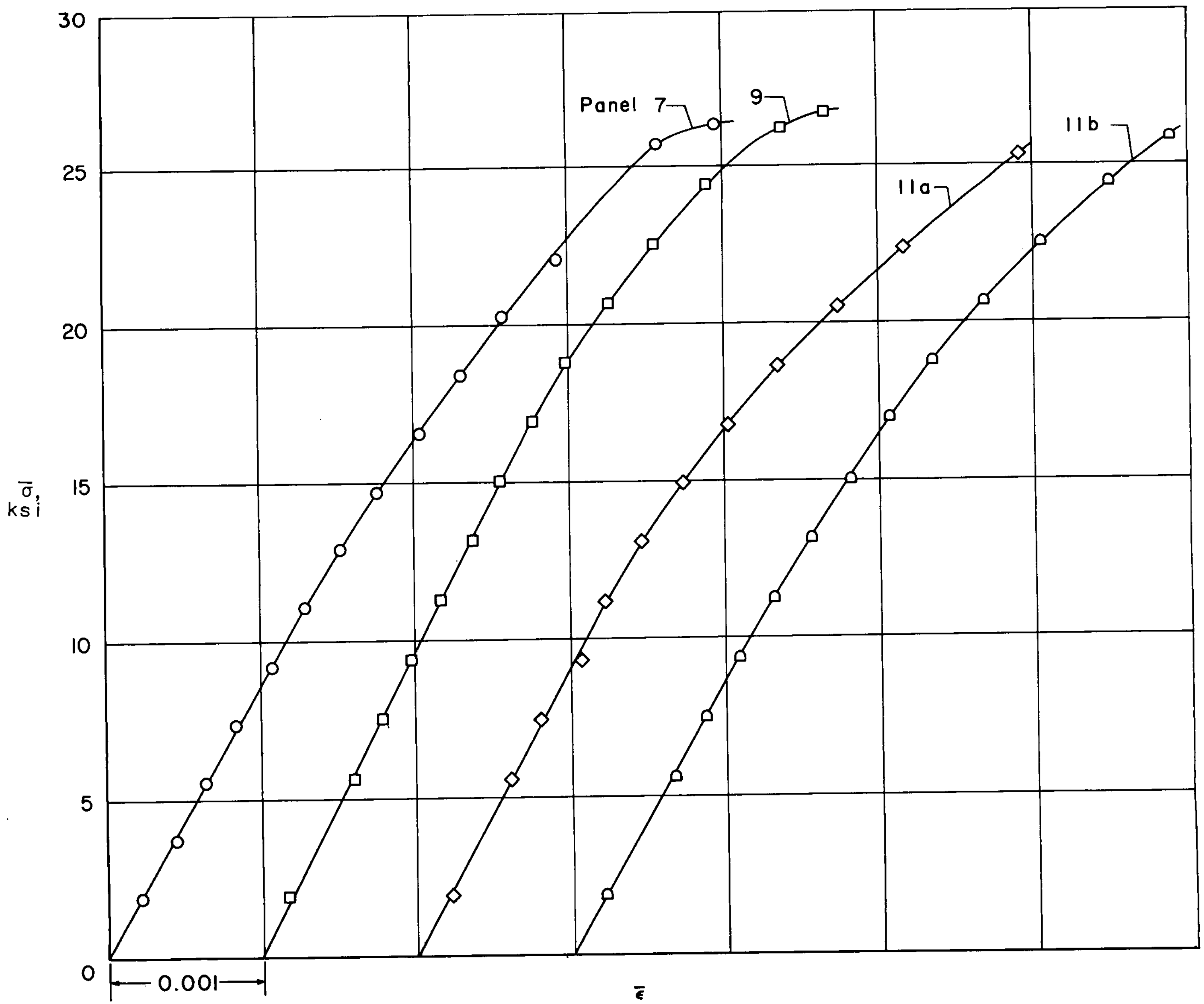
(b) Tube-on-sheet panels.

Figure 9.- Concluded.



(a) Tubed-sheet compression panels.

Figure 10.- Load-shortening curves.



(b) Tube-on-sheet compression panels.

Figure 10.- Concluded.

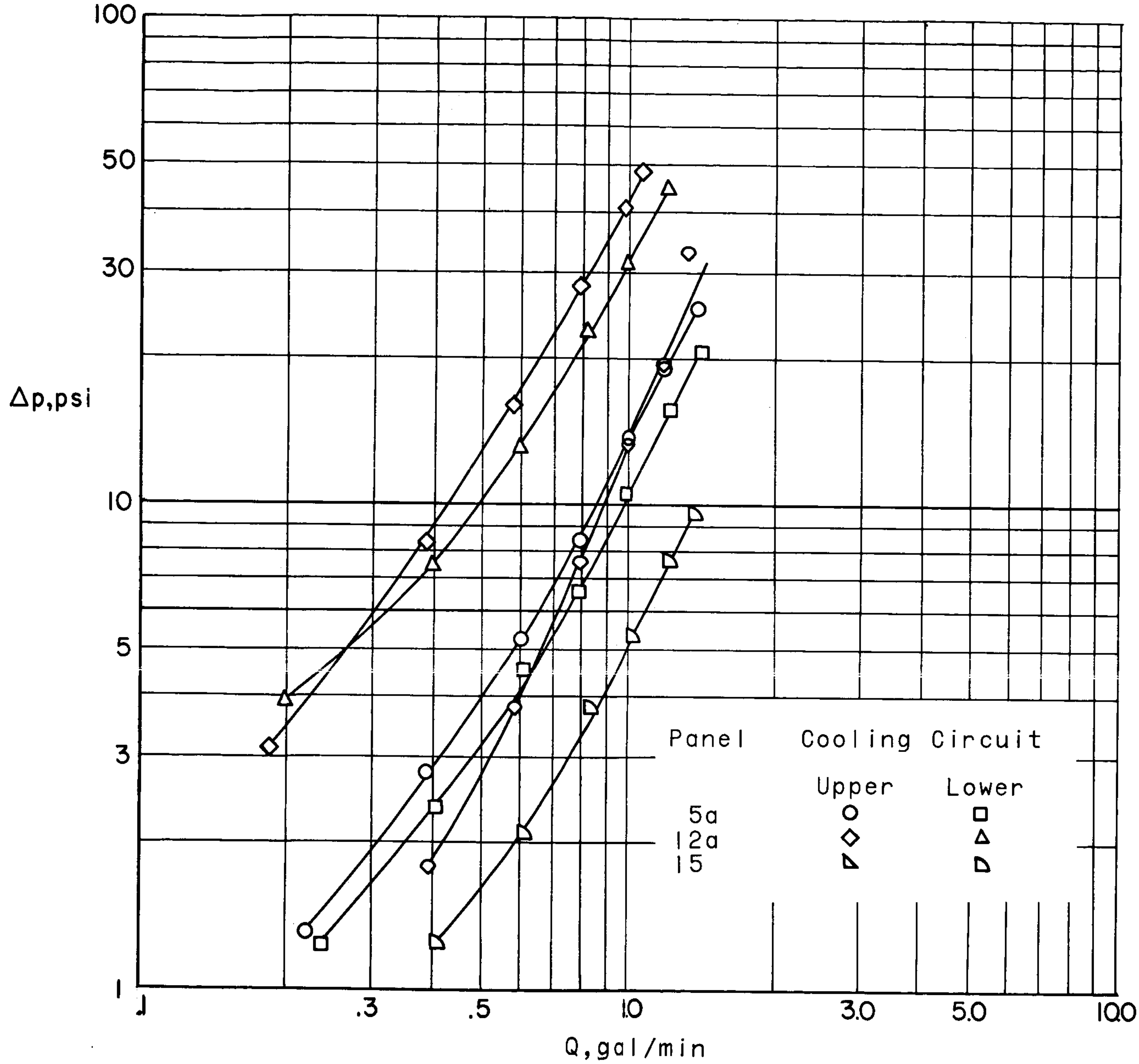
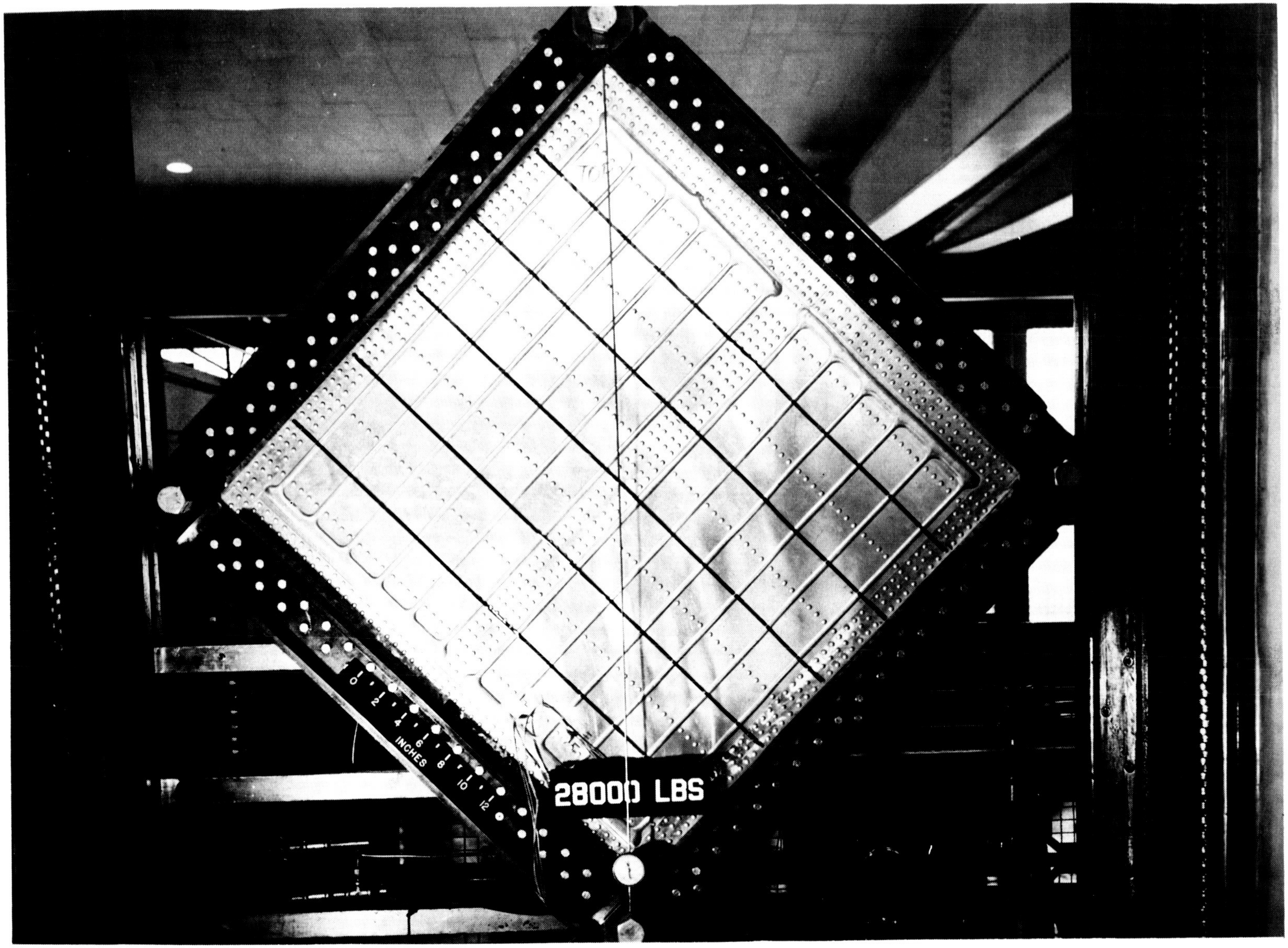
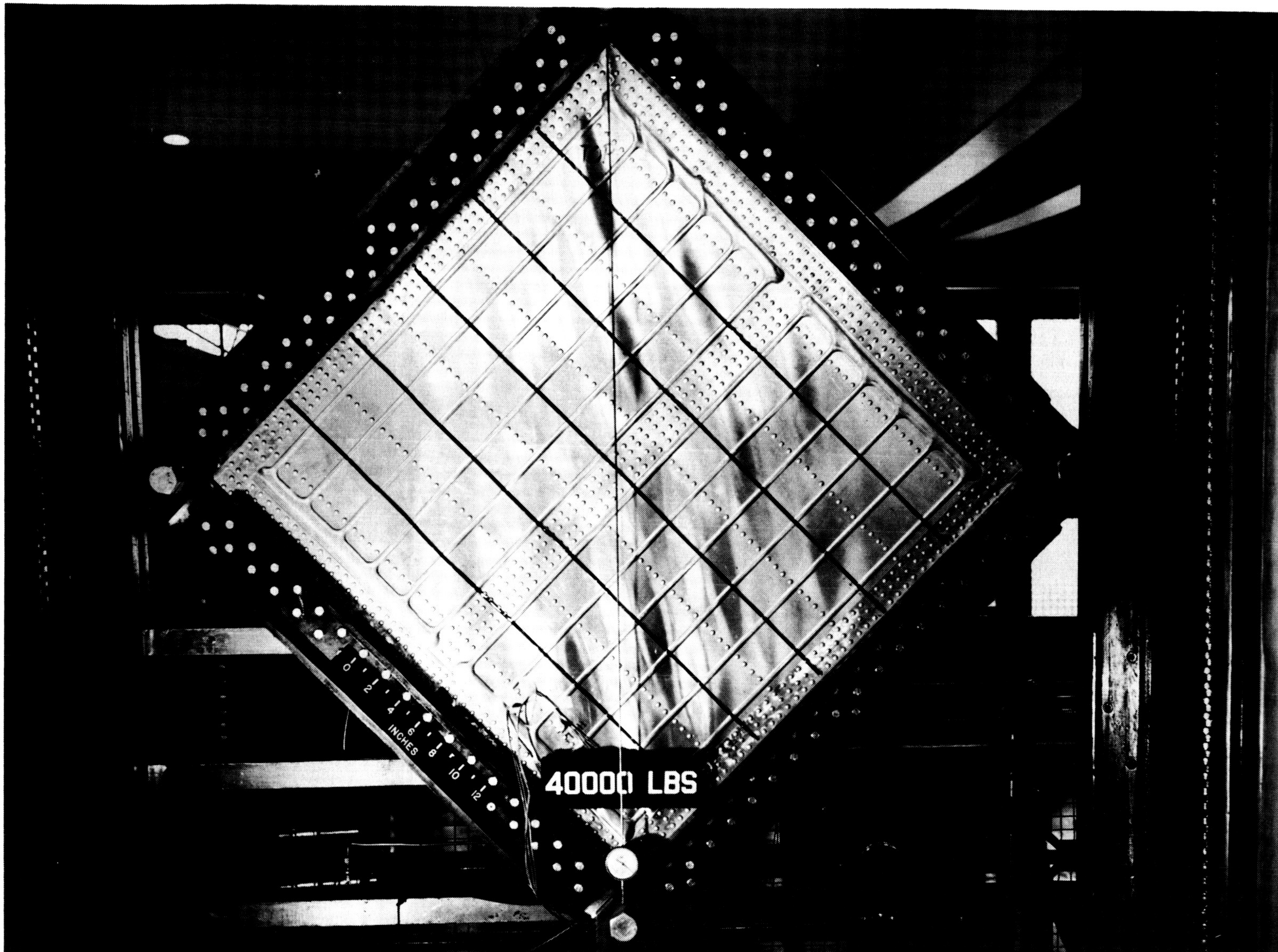


Figure 11.- Variation of differential pressure with flow rate.



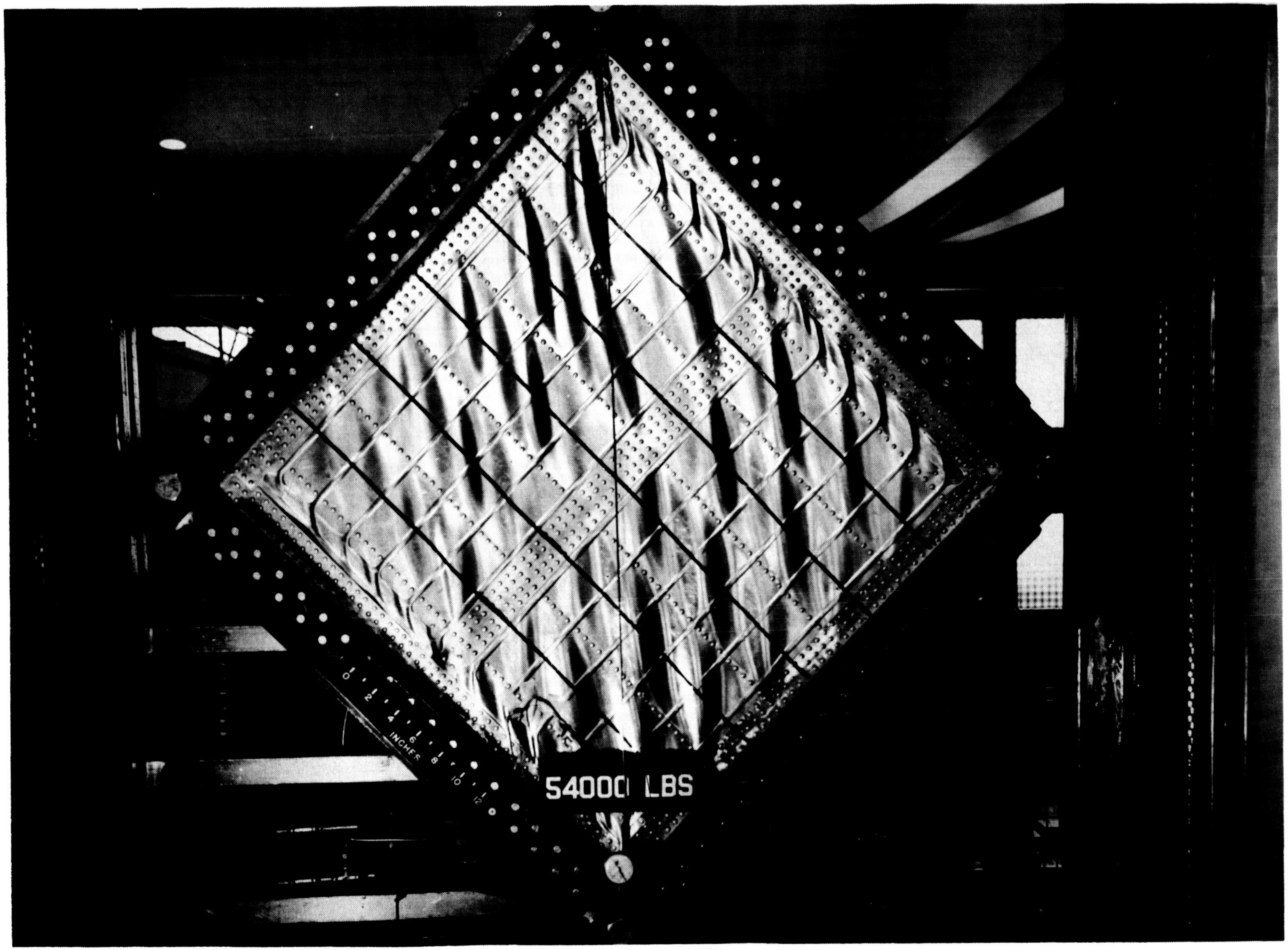
(a) Sheet buckling. L-60-4891

Figure 12.- Buckling of tubed-sheet shear panels.



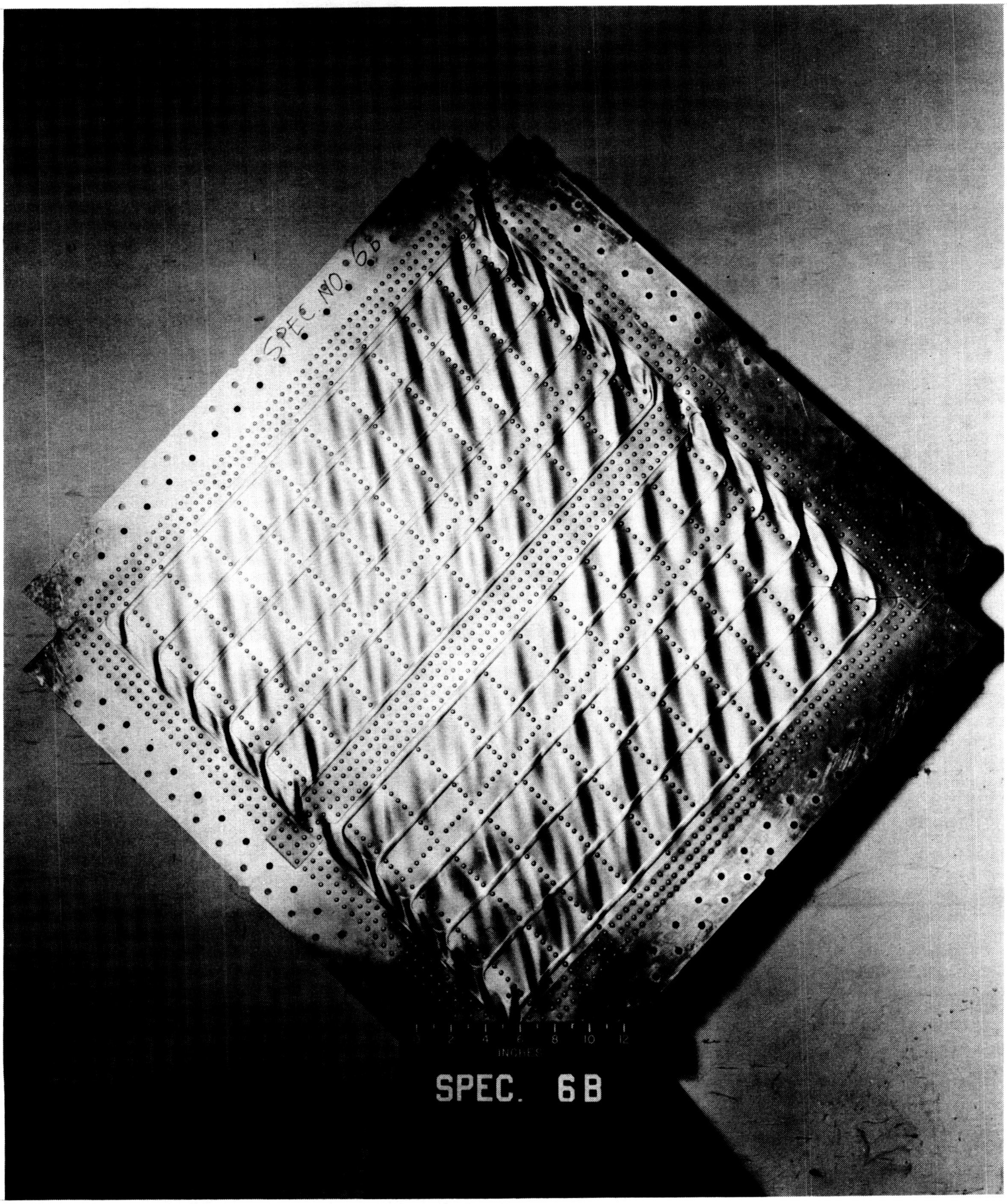
(b) Header and coolant-passage buckling. L-60-4893

Figure 12.- Continued.



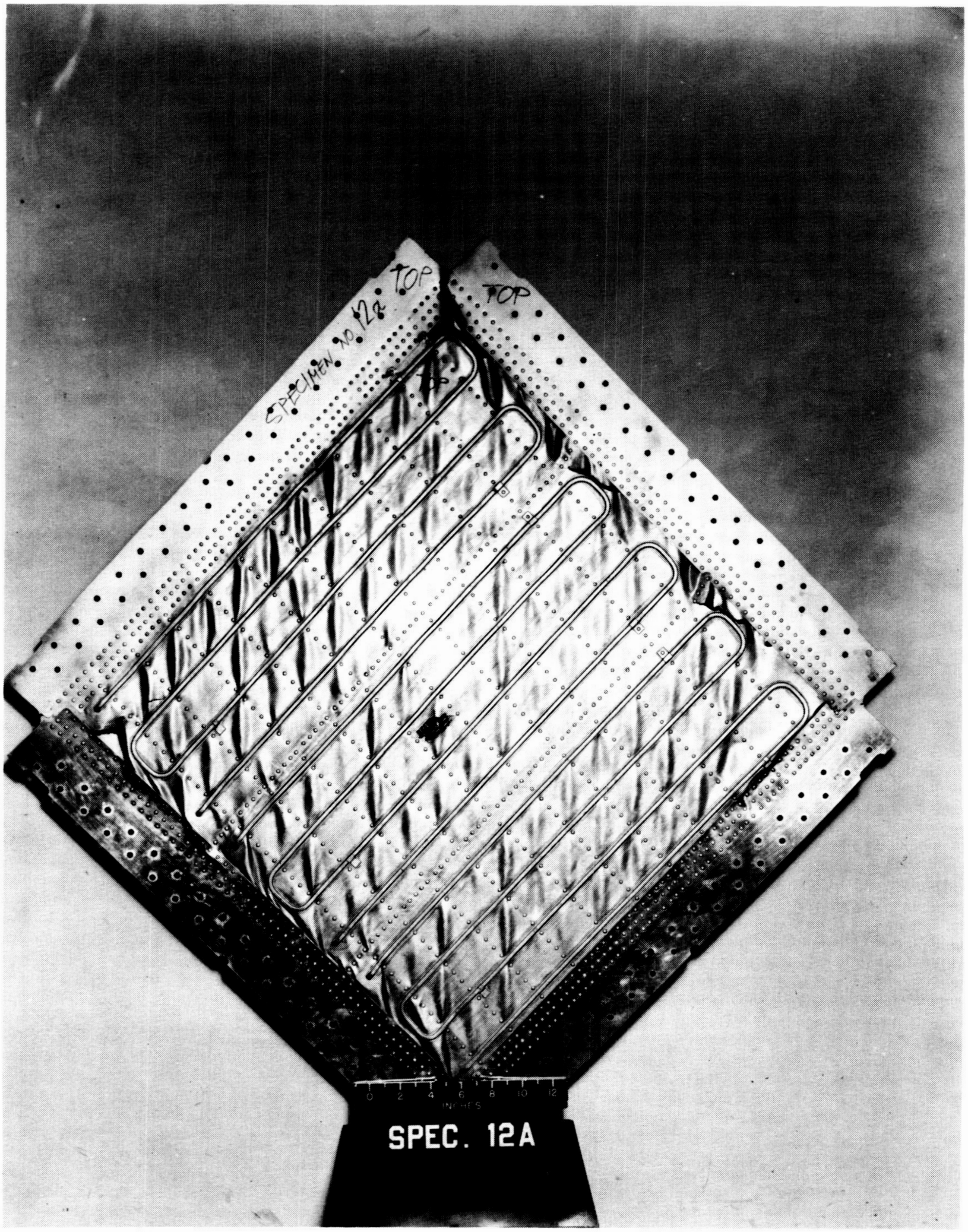
(c) Cooling-circuit crippling. L-60-4894

Figure 12.- Concluded.



(a) Tubed-sheet panel. L-60-5118

Figure 13.- Failure patterns in shear panels.



(b) Tube-on-sheet panel. L-60-5378

Figure 13.- Concluded.

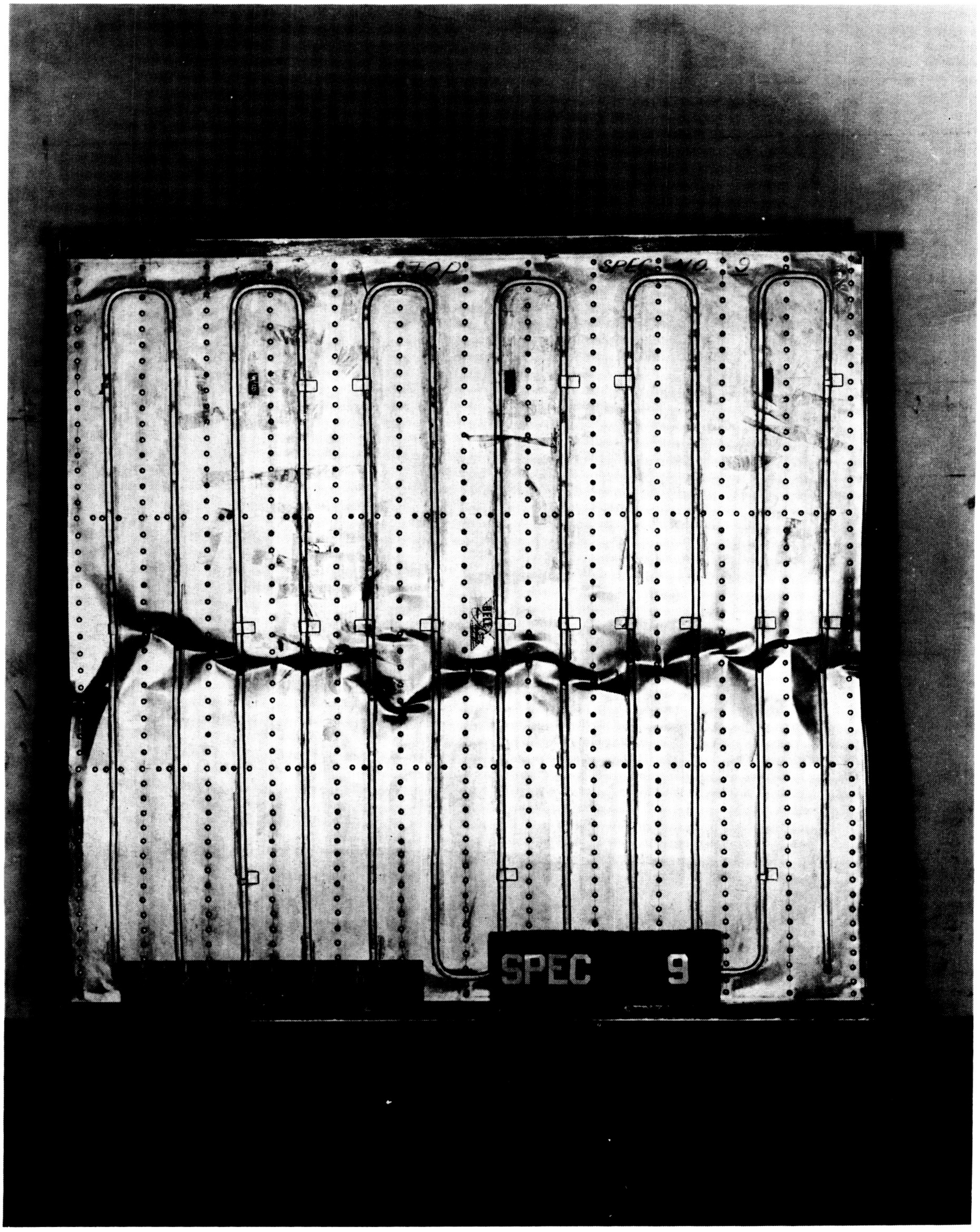
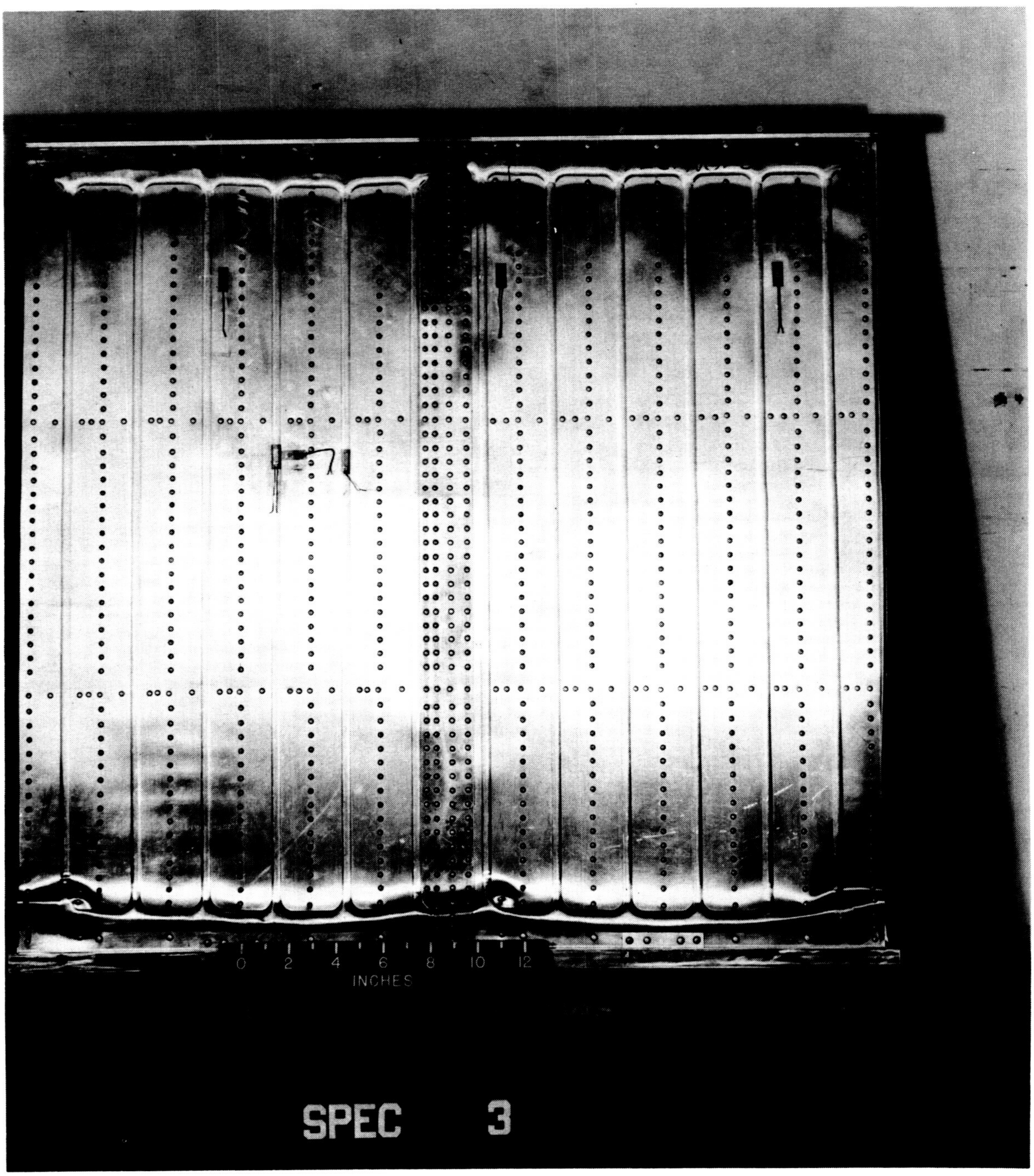
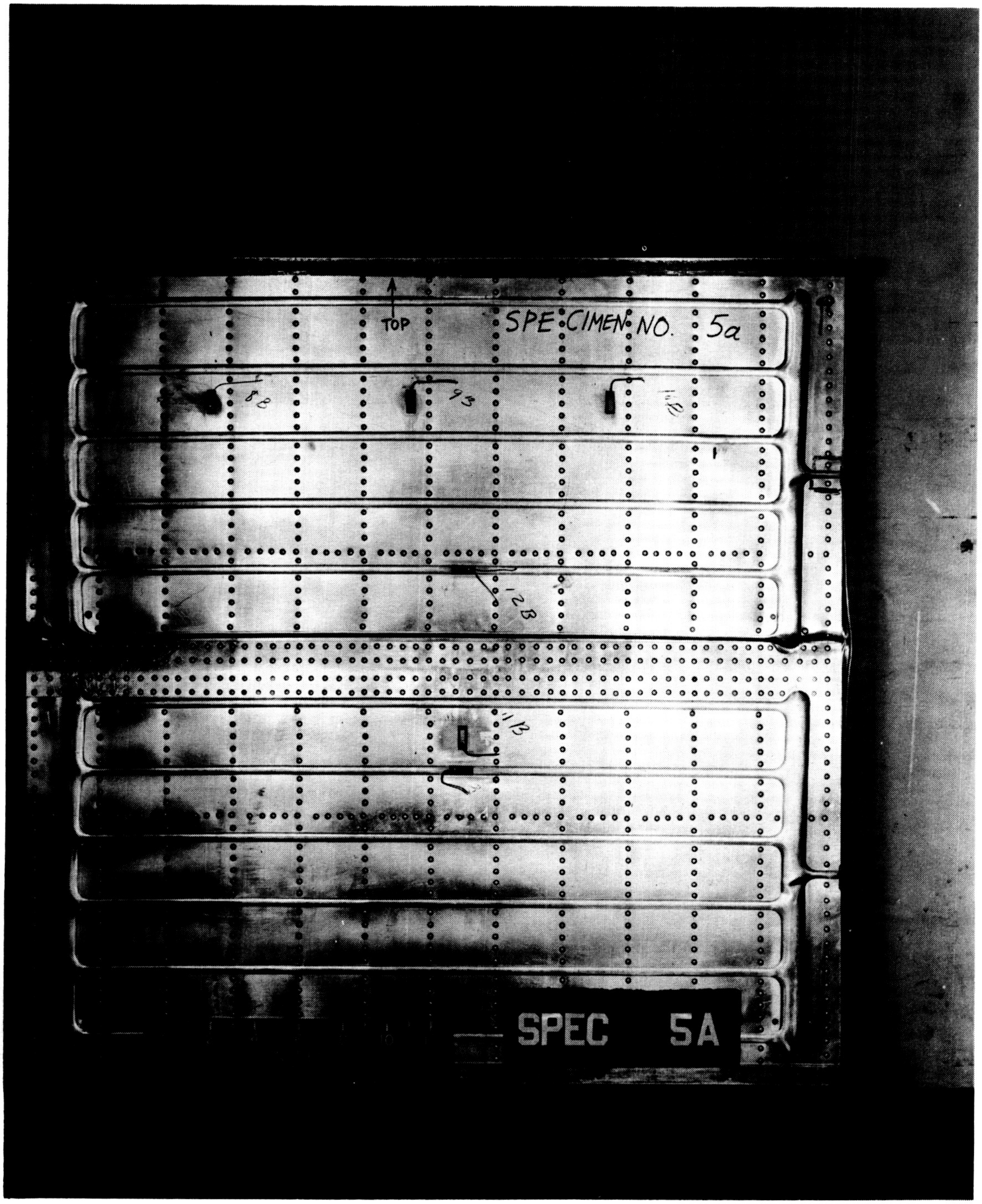


Figure 14.- Failure of compression panel in wrinkling mode. L-60-5663



(a) Failure near end of panel. L-60-5665

Figure 15.- Failure of compression panel in interrivet mode.



(b) Failure adjacent to center splice. L-60-5661

Figure 15.- Concluded.